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Hypervelocity Technology Escape System Concepts
Volume I. Development and Evaluation

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This report describes the results of a study conducted to develop crew escape system concepts for hypervelocity vehicles capable of transatmospheric missions. These escape system concepts were required to provide survivable escape and recovery throughout all phases of flight, including launch, upper atmospheric hypervelocity flight, orbit, reentry and terminal approach. The effort was divided into three tasks. In task I, 16 different concepts were studied to evaluate the feasibility of their meeting all the crew escape and protection requirements. The study vehicles included a horizontally-launched vehicle with dual-place cockpit and a vertically-launched vehicle with a single-place cockpit. Only 3 of the 16 concepts were determined to be viable options. A preliminary evaluation reduced the possible escape system candidates to two; an encapsulated seat with thermal protection and an escape capsule with thermal protection.

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In task II, various advanced technologies were investigated for possible application to the HVT crew escape concepts design development. These technologies included aerodynamics, thermal protection, propulsion, structures, materials, flight controls, sensors, crew station design, and life support. The results from this technology evaluation were used to refine the subsystem designs during task III, so that the design requirements were satisfied with minimum penalties to the vehicles. Trade studies were then conducted to select the best escape system concepts. These showed that the encapsulated seats were overall superior to the pod capsules for both study vehicles. Technical engineering support to AFWAL/FIER was provided by the Aeromechanic Division of the Flight Dynamics Laboratory (AFWAL/FIM) and by the Biodynamic Protection Branch of the Harry Armstrong Aerospace Medical Research Laboratory (AAMRL/BBP). Additionally AAMRL/BBP provided partial funding during FY86 under Program Element No. 62202F, Project No. 7231, Task No. 31, Work Unit Accession No. 114.

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1.0 INTRODUCTION

1.1 PROBLEM

The hypervelocity technology (HVT) vehicles of the future will have the capability of flying at much higher altitudes and much faster speeds than the current military aircraft. Moreover, they may have the capability of being in orbit for one to three orbits. Correspondingly, the escape systems for the HVT vehicles need to be designed for a much broader flight envelope than the existing escape systems for the military airplanes. Figure 1.1-1 shows the flight envelopes being used for the next state-of-the-art ACECT escape capsule (Reference 1) and the CREST demonstration ejection seat (Reference 2). As may be noted, the ACECT capsule and the CREST ejection seats are being designed for a maximum Mach Number of 3, while the HVT vehicles may be flying up to Mach Number of 25. These higher values of Mach no. result in significantly higher stagnation temperatures, so that the HVT vehicles and their escape system structure will be exposed to very high surface temperatures. For example, the uncooled structure temperatures in high heat areas may be in the 4,000°F to 6,000°F range at Mach 25 compared with about 600°F at Mach 3, depending upon the aerodynamic shape, the surface emissivity and surface catalicity.

The higher operating altitude of the HVT vehicles will result in the crew emergency support systems being designed to provide oxygen, pressurization and temperature control for a much longer period.

Although many studies have been conducted under NASA sponsorship to develop escape system concepts to rescue crewmembers from vehicles in orbit (References 3-6), these escape systems have not actually been built or tested. The basic problems to be solved are protection against high temperature during reentry, and the volume and weight requirements imposed upon the HVT vehicle by the escape system.

A successful escape during reentry into the atmosphere imposes additional requirements on the design of a crew escape system. For example, if a capsule is designed to be stable with its heat shield pointed forward, but has the heat shield pointed aft during normal flight, then the heat shield will be pointed in the wrong direction for some time after escape initiation. This will result in higher surface temperatures at some capsules locations, compared with the surface temperatures for escape prior to atmospheric reentry.

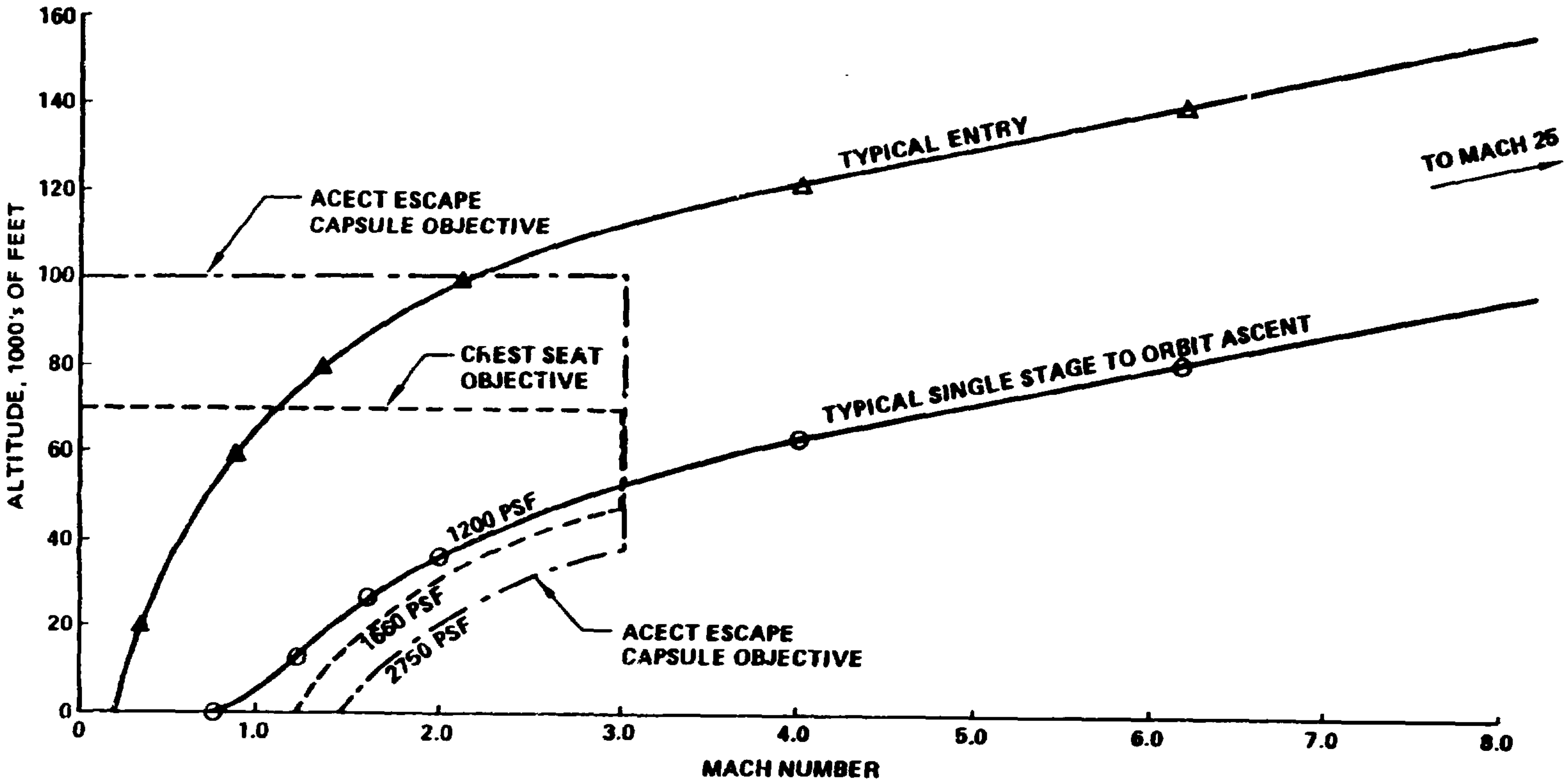


Figure 1.1-1. Ejection Seat and Capsule Performance Envelopes with Typical-Single-Stage-to-Orbit Ascent and Entry Profiles Shown to Mach 8

The HVT vehicles may be susceptible to em ˏgency situations, such as an explosion, at launch or just before launch, which are different from those for a typical airplane during takeoff. To provide protection against such emergencies, the escape system must quickly remove the crewmembers to enough distance away from the vehicle, so that they are safe from the serious effects of the shock wave, if some time to do so is available.

Some HVT vehicle escape system design considerations are similar to those for the conventional airplane escape systems. These include separation at high dynamic pressure, stability, impact attenuation, crew member accelerations, adequate restraint, crew station integration, parachute opening dynamics, windblast protection, reliability and maintainability.

The volume and weight requirements imposed upon the HVT vehicle by the escape system are very important design considerations. The payload of the HVT vehicles to be studied under this program is as low as one percent of the total takeoff weight. Any weight added to these vehicles to provide crew escape capability will have a major impact on the payload. It is, therefore, imperative that a major emphasis be placed on keeping the escape system weight down.

1.2 PROGRAM OBJECTIVES

The objectives of the HVT Escape System Concepts program were to:

a. Develop crew escape system concepts for hypervelocity vehicles capable of transatmospheric missions. These escape system concepts were designed to provide survivable escape and recovery throughout all phases of flight, including launch, upper atmospheric hypervelocity flight, orbit, reentry and terminal approach. Capability was desired to:

    1. Allow recovery within the continental United States for escape initiated from orbit.
    2. Allow for extended cross range flight for escape initiated during upper atmospheric hypervelocity flight.
    3. Allow for immediate recovery anywhere for all other other escape conditions.

b. Investigate the latest developments in the supporting technologies of aerodynamics, thermal protection, propulsion, advanced structures, high temperature materials, flight controls, life support, crew protection, and crew station design for possible incorporation into the selected crew escape concepts.

c. Conduct trade studies to determine the best escape concepts for a horizontally launched vehicle with dual-place cockpit and a vertically launched vehicle with

single-place cockpit. The key factors used to select the best concepts included escape system performance, system weight, volume requirements, integrability with the cockpit and the vehicle, reliability, maintainability, safety, development risk and cost.

1.3 PROGRAM OVERVIEW

As shown in Figure 1.3-1, the HVT Escape System Concepts program consisted of 3 major tasks:

- o Task I - Concepts Definition and Preliminary Evaluation
- o Task II - Advanced Technologies Evaluation
- o Task III - Concept Trade Study

The technical approach used to develop and evaluate escape system concepts for HVT vehicles is outlined in Figure 1.3-1. The principal features of this approach are discussed below. The details of the accomplished work are given in Sections 2.0 through 9.0.

The first major subtask was to select the two HVT vehicles to be used for the development of the crew escape concepts. Various HVT vehicle configurations have been and are being studied by Boeing under various contracts. Two of the most suitable ones of these, one horizontally launched and the other vertically launched, were selected for this study. These vehicles are discussed in Section 2.1.

The next step was to generate typical flight profiles and establish the flight envelopes for the two vehicles. The results are discussed in Section 2.2. The subsystem hazard analysis is presented in Section 2.3. The resulting crew escape requirements are described in Section 3.1.

The crew protection requirements to be used for the study were also established, and are discussed in Section 3.2. These include appropriate limits on accelerations, angular rates, total pressure and oxygen partial pressure, carbon dioxide, environmental temperature, ionizing radiation, windblast and exposure to shock waves. The candidate escape concepts must satisfy the crew protection requirements for all escape conditions in the flight envelopes of the study HVT vehicles.

Various escape system concepts were screened for their possible ability to satisfy all the requirements over any part of the HVT vehicle escape envelopes. The salient features of these concepts and their evaluation are discussed in Section 4.0. Only the promising concepts were developed further. The complete escape operation of these concepts is described in Section 5.0.

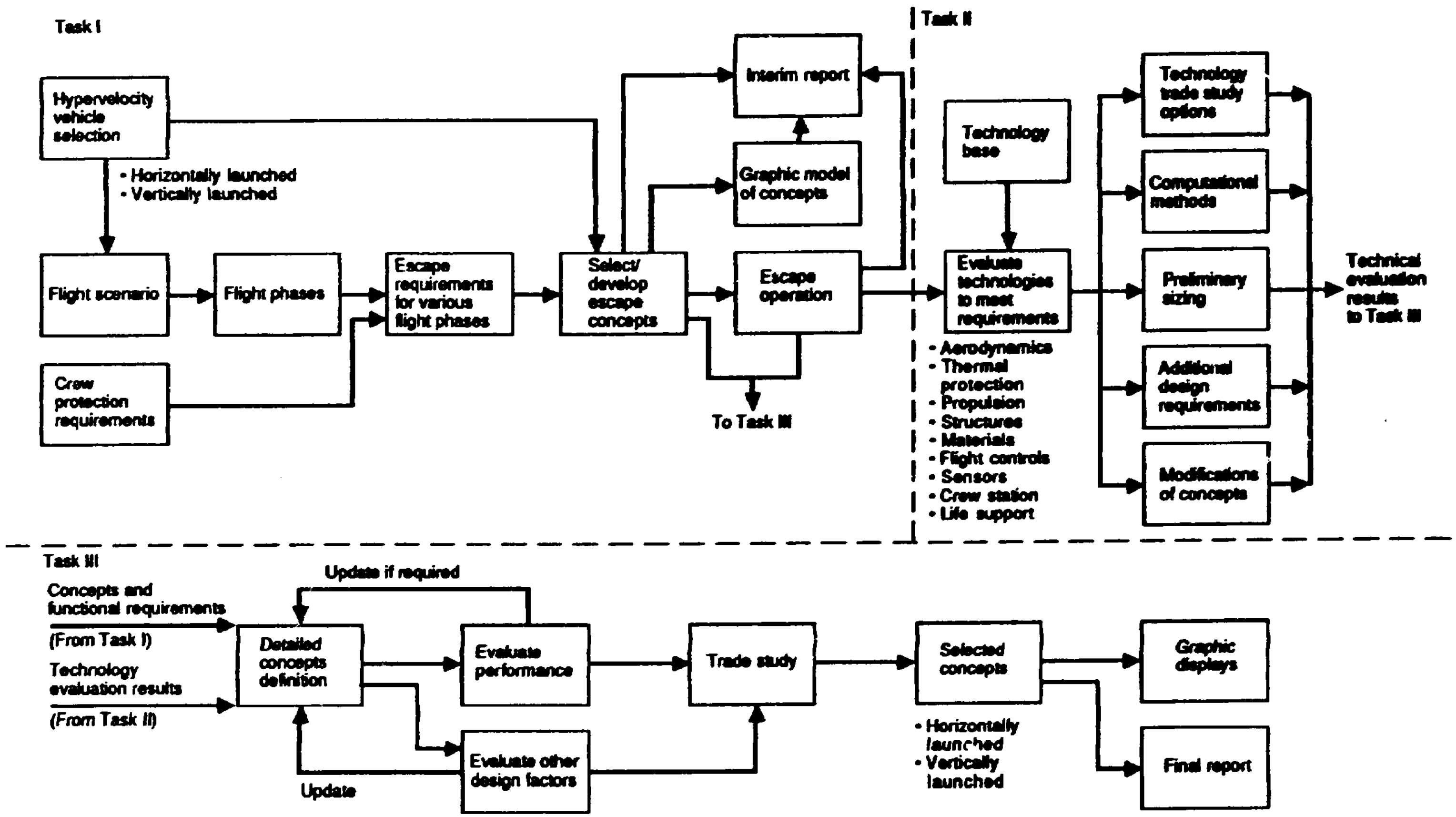


Figure 1.3-1. HVT Escape System Concepts Development Flow Chart

As part of Task II, various advanced technologies were investigated for possible application to the HVT crew escape concepts design development. These technologies included aerodynamics, thermal protection, propulsion, structures, materials, flight controls, sensors, crew station design and life support. The advances in computational tools available for better predicting the characteristics of the escape concepts were also examined as part of the technology investigation. The current status of the applicable technologies is discussed in Section 6.0.

Preliminary sizing of the subsystems associated with each HVT escape system concept was done during Task II. Subsequently, the subsystem designs were refined during Task III to ensure that the design requirements and objectives were satisfied with minimum penalties to the vehicles. Details of this escape concept definition, sizing, and the resulting weight and inertial properties are given in Section 7.0.

A design decision matrix approach was used to conduct the trade studies for the best escape system concepts for the HLV and the VLV. The design factors, weighting factors and merit scales used for the trade study are discussed in Section 8.0. The results of the trade study, including the concept performance evaluation are described in Section 9.0. The conclusions and recommendations of the study are presented in Section 10.0.

2.0 HYPERVELOCITY VEHICLE CONFIGURATIONS AND FLIGHT PROFILES

The selection of the hypervelocity vehicles used for developing escape concepts is discussed in Section 2.1. The corresponding flight profiles and envelopes are discussed in Section 2.2. The subsystem hazard analysis is presented in Section 2.3.

2.1 HYPERVELOCITY VEHICLE CONFIGURATIONS

The hypervelocity technology (HVT) vehicle configurations to be used for escape system development included a horizontally launched vehicle and a vertically launched vehicle. Each vehicle configuration was required to allow missions of 1 to 3 orbit durations, including one upper atmospheric braking maneuver to change the orbital plane.

In addition, the horizontally launched HVT vehicle was required to:

- Provide for 2 crewmembers in the cockpit
- Allow for a payload equal to 1 percent or more of the total takeoff weight.

The vertically launched HVT vehicle was required to:

- Provide for 1 crewmember in the cockpit
- Allow for a payload approximately equal to 1 percent of the total takeoff weight of approximately 1.3 to 1.6 million pounds

The horizontally launched HVT vehicle selected for this study is shown in Figure 2.1-1, with some of the details shown in Figure 2.1-2. It is a single-stage-to-orbit vehicle and makes extensive use of combined cycle airbreathing propulsion.

The vertically launched HVT vehicle selected for this study is shown in Figure 2.1-3. It is a 2-stage vehicle. It was originally designed for a two-man crew orbiter and an unmanned booster. For this program, the orbiter cockpit has been modified to accommodate only one crewmember. This vehicle has a gross lift-off weight of 1.58 million pounds and a payload of 15,000 pounds. Liquid hydrogen and liquid oxygen are used as propellants for both the booster and the orbiter. The total propellant weight is 1.1 million pounds for the booster and 204,000 pounds for the orbiter. Some of the details of the orbiter are provided in Figure 2.1-4.

For both vehicle configurations, active cooling of the vehicle critical areas and compartments, such as the crew cabin, is required during flight at high Mach number or during atmospheric reentry to keep the temperatures at an acceptable level.

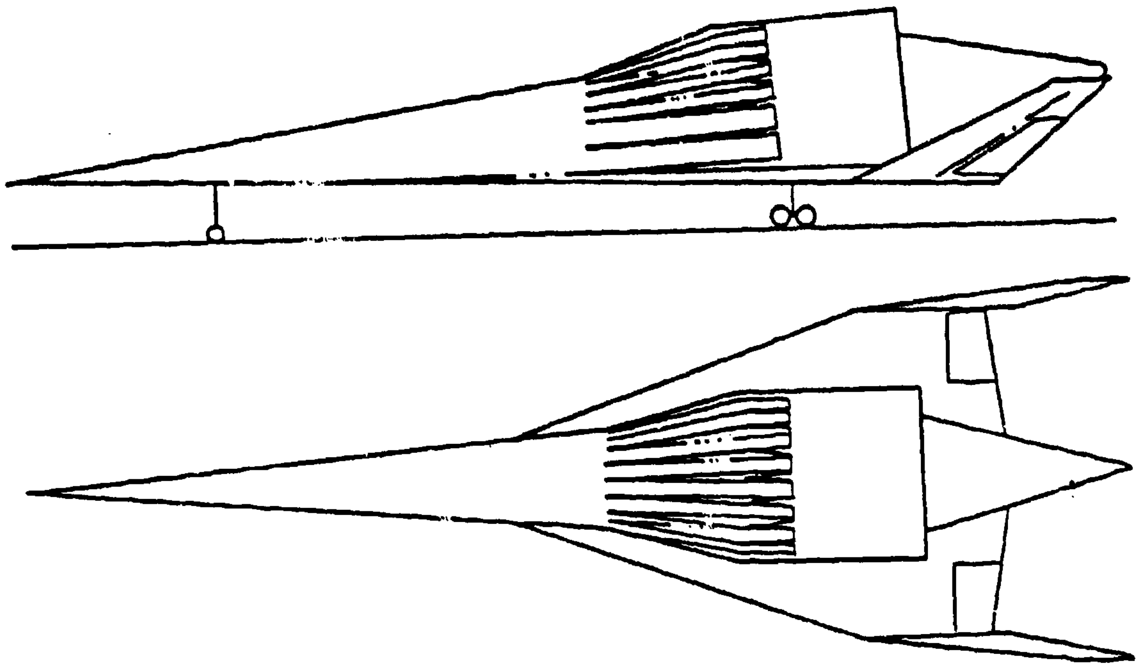


Figure 2.1-1. Selected Horizontally-Launched HVT Vehicle Configuration

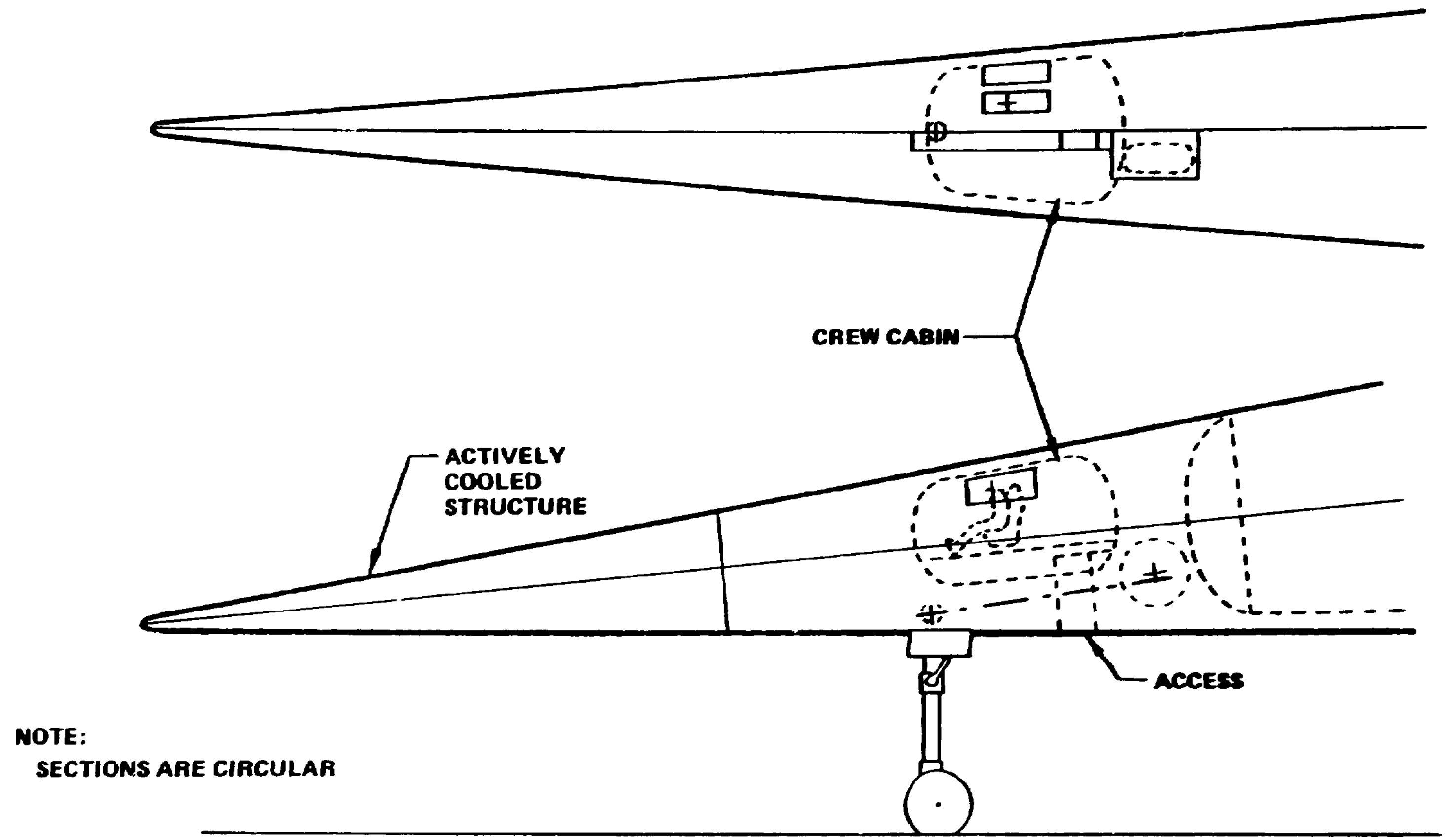


Figure 2.1-2. Horizontally-Launched HVT Vehicle Details

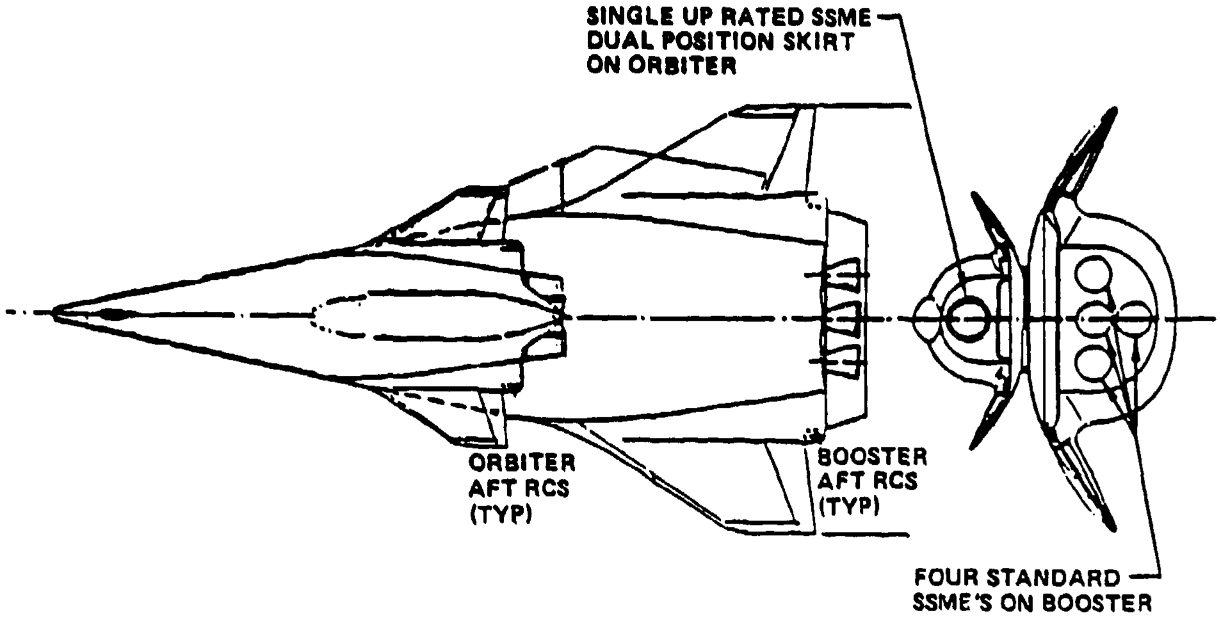


Figure 2.1-3. Selected Vertically-Launched HVT Vehicle Configuration

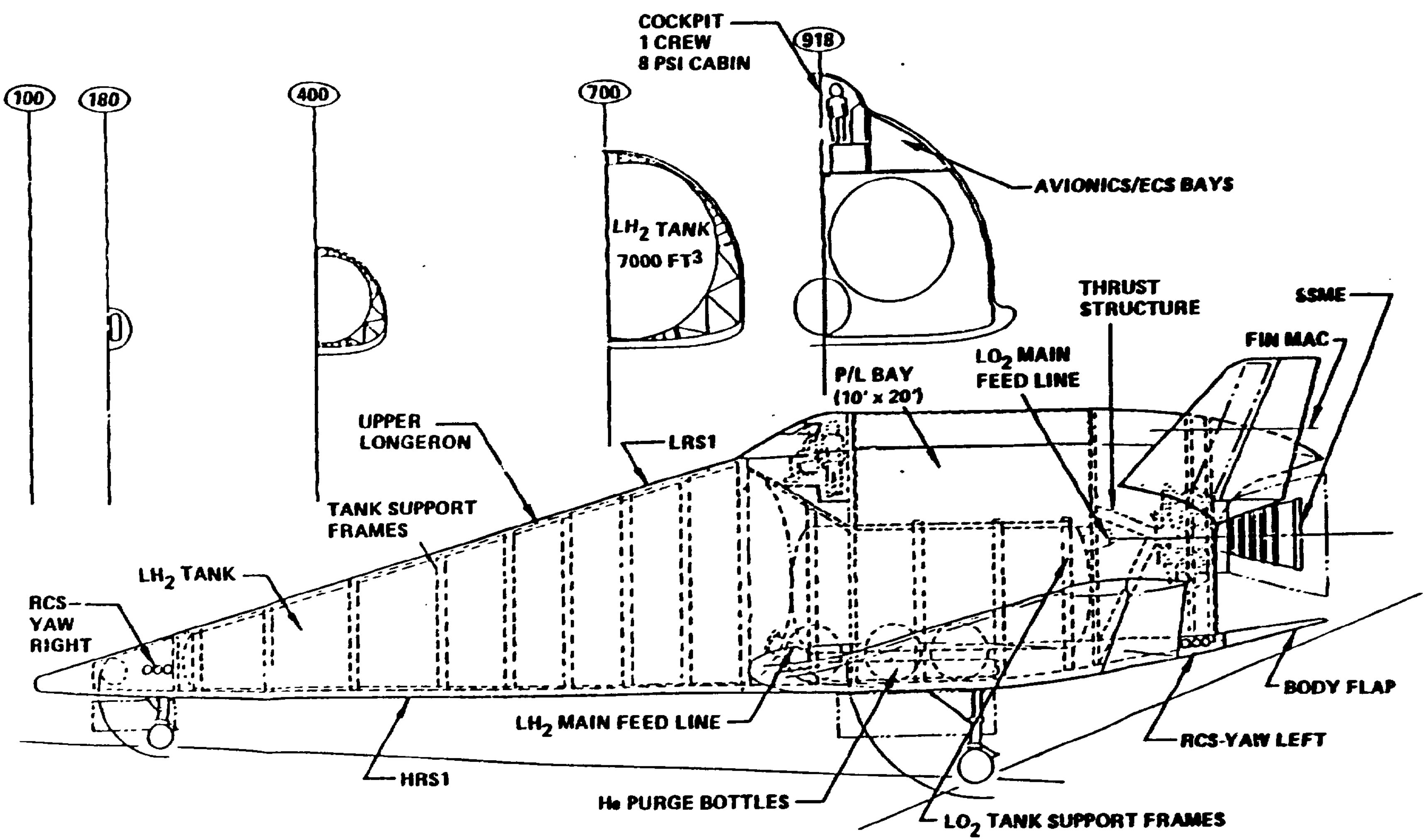


Figure 2.1-4. Orbiter for the 2-Stage Vertically-Launched HVT Vehicle

2.2 HYPERVELOCITY VEHICLE FLIGHT PROFILES

The flight profiles for the horizontally launched and the vertically launched HVT vehicles are described in Sections 2.2.1 and 2.2.2 respectively.

2.2.1 Flight Profiles For Horizontally Launched Vehicle

2.2.1.1 Ascent and Descent Profiles

Typical ascent profiles for the horizontally launched vehicle (HLV) are shown in Figures 2.2-1 and 2.2-2. Figure 2.2-1 shows the plot between the vehicle altitude and its velocity, while Figure 2.2-2 shows the plots for dynamic pressures, reference heating rate, longitudinal acceleration and flight time as a function of the vehicle velocity. During takeoff, a dynamic pressure placard of 1200 lbs/sq. ft. is followed to Mach 12, at which point the flight path steepens to gain altitude. Airbreathing propulsion will probably cease around 200,000 feet and Mach 25. From that point on, a transition is made with the aid of rocket propulsion into a higher orbital altitude of 100 to 300 nmi.

A typical atmospheric entry path for this vehicle is shown in Figures 2.2-3 and 2.2-4. The value of the ballistic coefficient, $W/(C_d.A)$, for this path was 360 lb/ft^2; W, C_d and A being the vehicle weight, the coefficient of drag and the reference area respectively. Note that the reference heating rates and the dynamic pressure are considerably lower than for airbreathing ascent paths. The curves shown are smoothed to eliminate some of the flight path oscillations that normally occur during the first few minutes of entry.

An examination of Figures 2.2-1 and 2.2-2 shows that for this ascent profile, a speed of Mach 3 is reached in about 25 minutes at an altitude of about 60,000 feet. The hypersonic ascent phase from Mach 3 to Mach 25 lasts nearly one hour. Because of this long "soak" period, heating may be a much greater problem during ascent than during the reentry. The maximum longitudinal acceleration during the ascent phase is about 1 g. The maximum vertical acceleration (not shown in Figures) is also about 1 g.

The hypersonic descent or reentry phase from Mach 25 at 300,000 feet to Mach 3 at about 120,000 feet takes about 50 minutes.

The overall flight corridors for the horizontally launched HVT vehicle are shown in Figure 2.2-5. The lower corridor applies to ascent flight paths; the upper to entry paths. The ascent corridor out to about Mach 20 is bounded by lines of constant dynamic pressure - 2000 psf on the lower bound and 800 psf on the upper. The entry boundaries envelop a variety of entry trajectories covering different crossranges and wing loadings. The maximum crossrange for the vehicle is about 2,500 nmi.

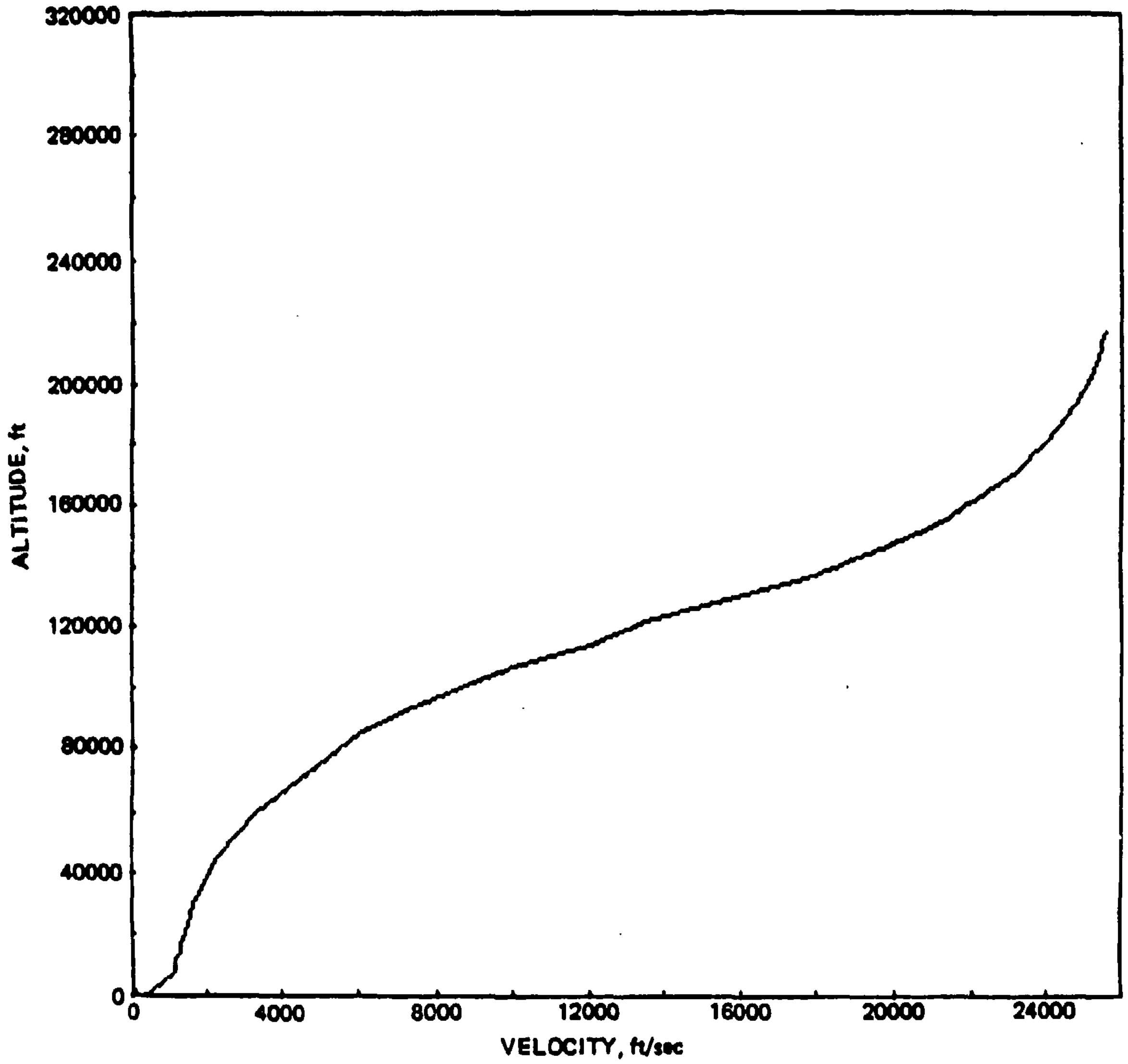


Figure 2.2-1. Single-Stage-to-Orbit Acsent Path for Horizontally-Launched HVT Vehicle

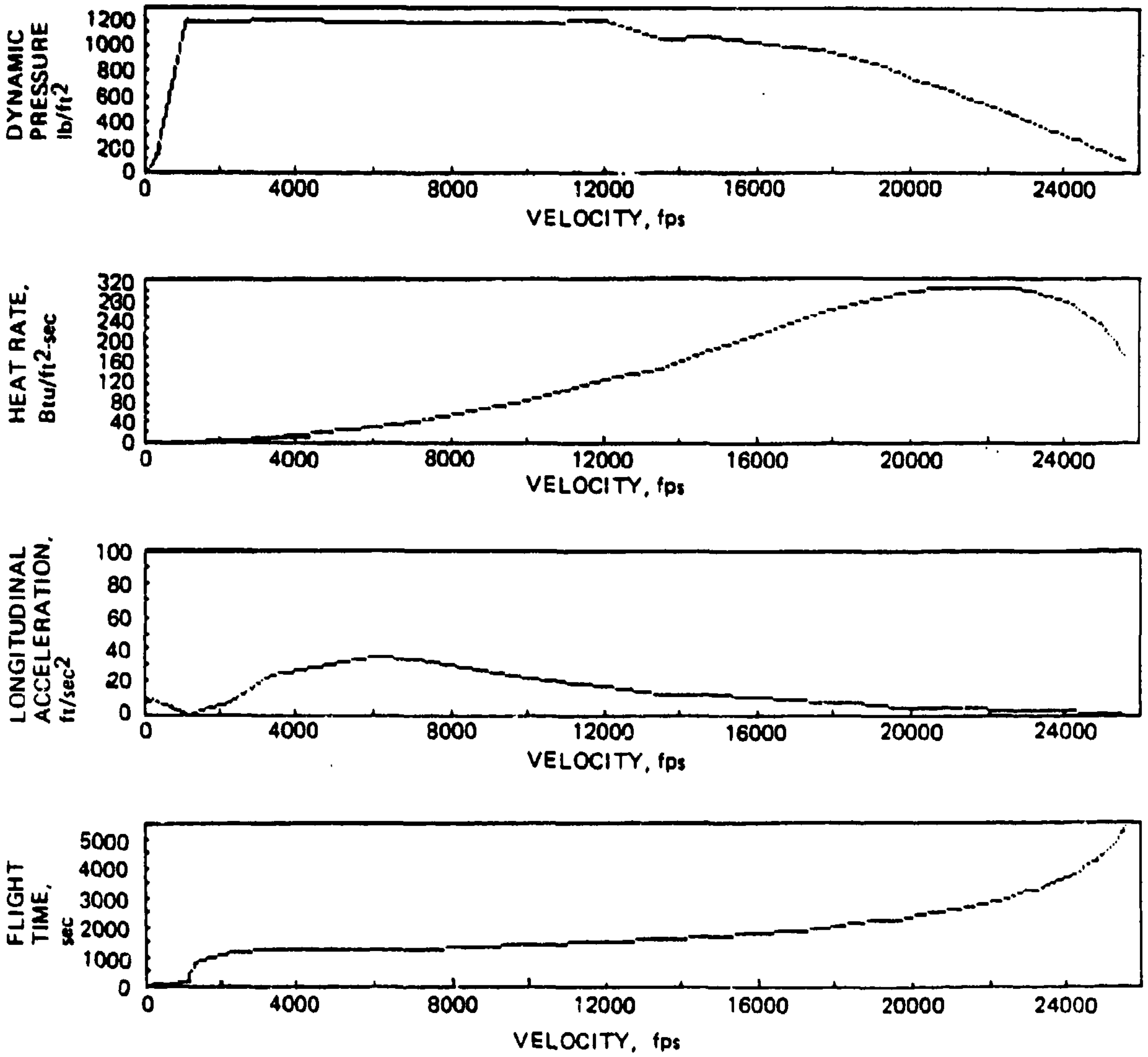


Figure 2.2-2. Single-State-to-Orbit Flight Data for Horizontally-Launched HVT Vehicle

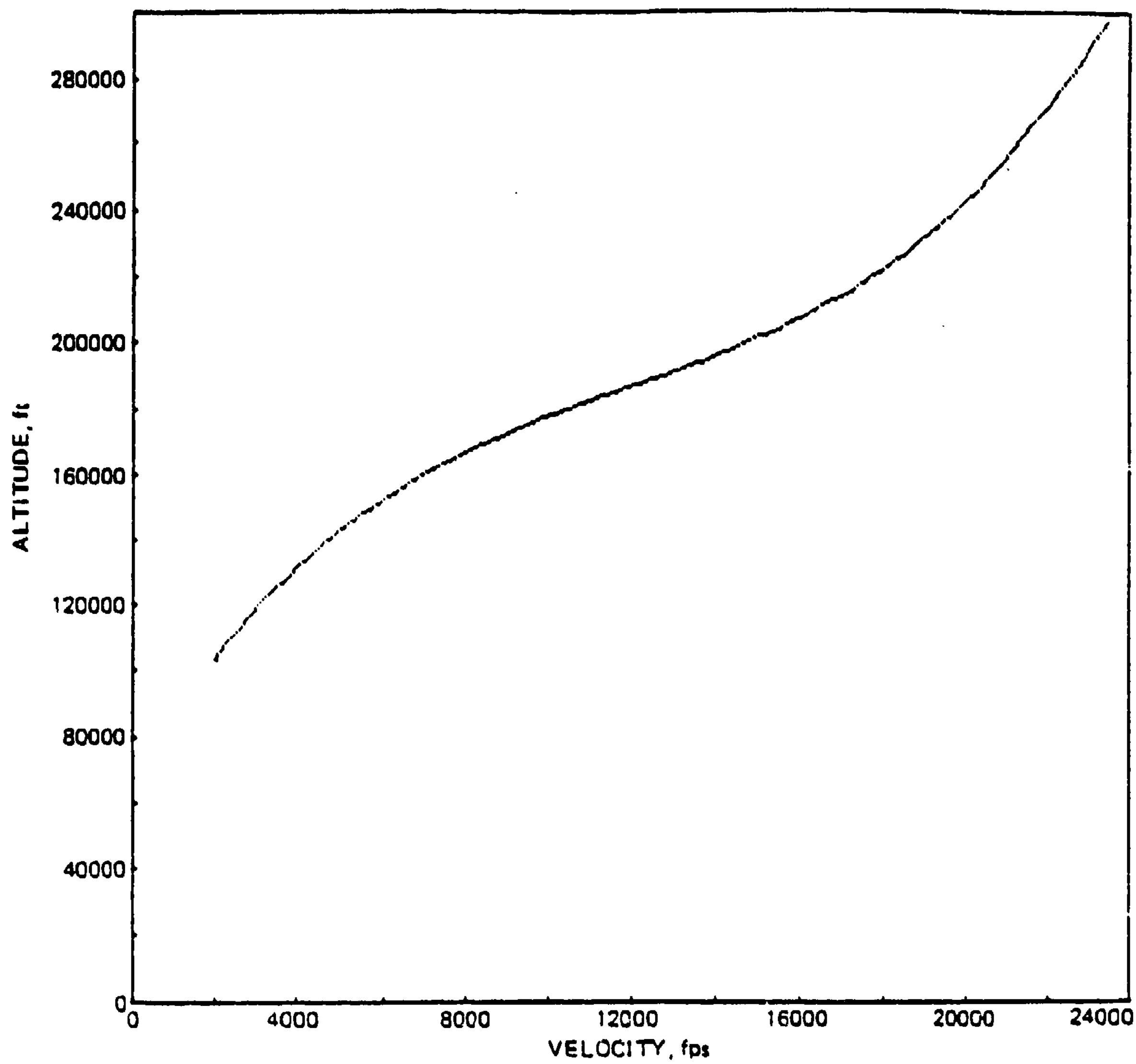


Figure 2.2-3. Typical Entry Flight Path for Horizontally-Launched HVT Vehicle

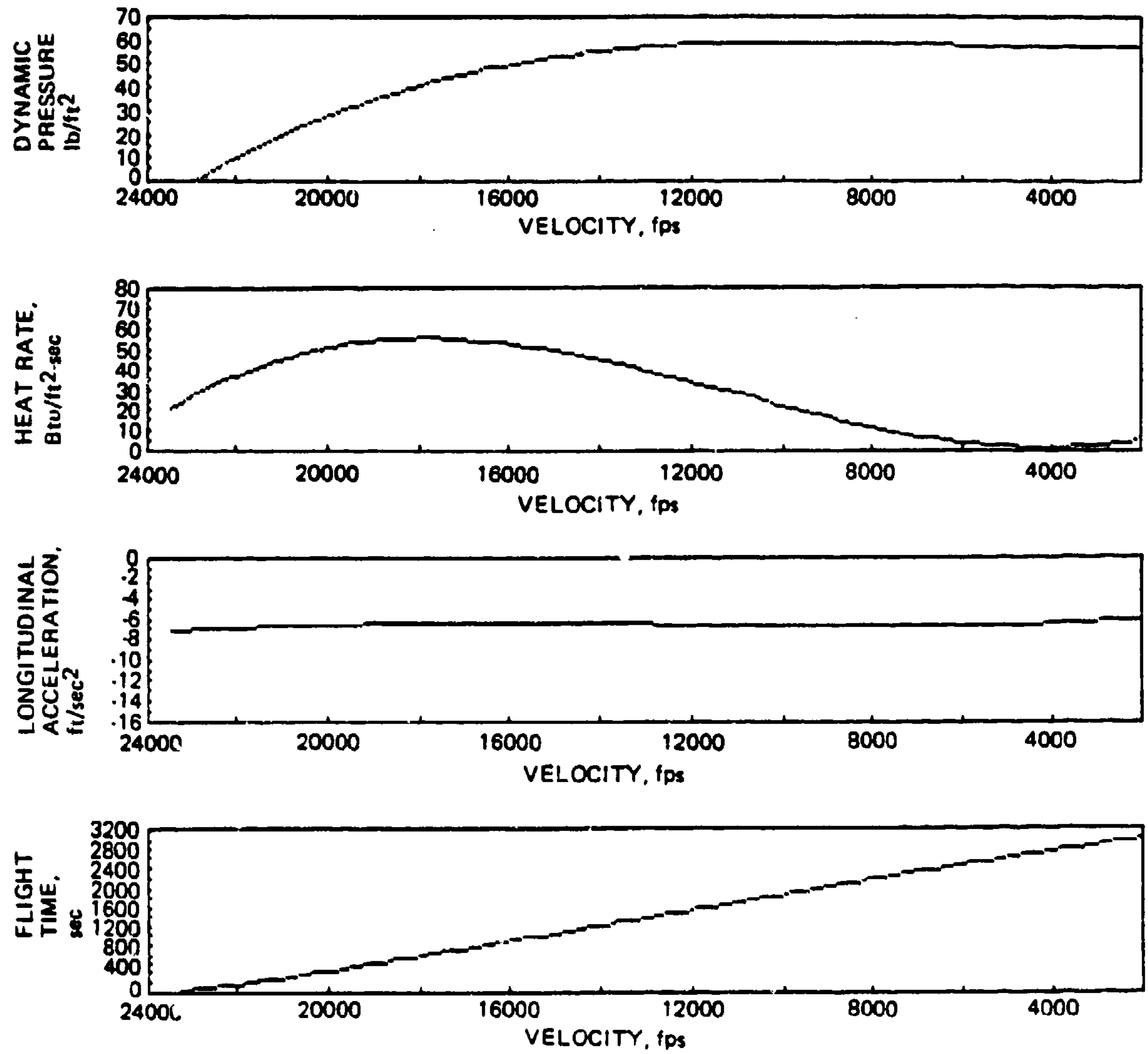


Figure 2.2-4. Single Stage-to-Orbit Entry Flight Data for Horizontally-Launched HVT Vehicle

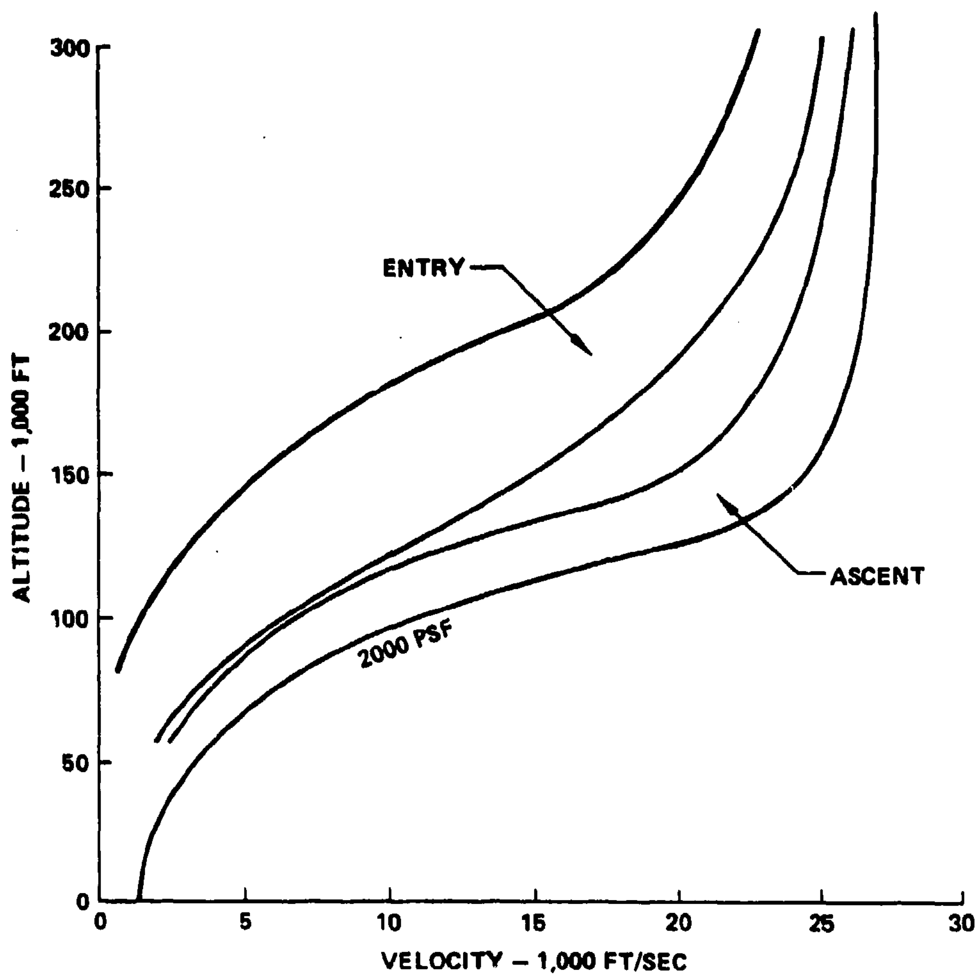


Figure 2.2-5. Flight Corridors for the Horizontally-Launched HVT Vehicle

2.2.1.2 High and Low Altitude Operations

The ability to takeoff from a runway and accelerate to a high Mach number at high altitudes enables the HLV to have an atmospheric mission without first going into orbit. The high altitude flight envelope is shown in Figure 2.2.-6. It may be noted that the vehicle is able to cruise up to Mach 20 at altitudes of 125,000 to 180,000 feet. At higher than 180,000 feet altitude, lack of sufficient lift for sustained hypersonic cruise makes the operation inefficient.

Lower altitude operations include takeoff, landing, and low altitude subsonic ferry flight. The vehicle has a takeoff speed of about 250 knots and a landing speed of about 200 to 230 knots. The landing flight path angle is about 3 to 3.5 degrees. The subsonic ferry flight will be at about 40,000 feet. The vehicle mission does not include sustained low altitude maneuvers close to the ground.

2.2.1.3 Orbital Plane Change Maneuver

The horizontally launched HVT vehicle makes a synergistic orbital plane change maneuver, which combines an aeromaneuver with propulsive thrust to achieve a plane change. A typical synergistic orbital plane change maneuver is shown in Figure 2.2-7. The maneuver starts with a deorbit burn. At atmospheric entry, the vehicle is rolled to 180 degrees and its lift is used to capture the vehicle into the atmosphere. The vehicle is then rolled with the bank angle being a function of the heating rate. Once the heating rate achieves approximately 70 percent of its maximum value, the bank angle is held constant. When the maximum value of the heating rate is met, a constant flight path is flown to maintain that heating rate. The reboost burn is begun while the vehicle is in the constant flight path angle phase. The time of burn initiation is chosen so that the burn is terminated at or above 250,000 feet and the trajectory reaches the desired apogee. During the burn, a pull-up maneuver is performed to lift the vehicle out of the atmosphere. Following the reboost burn, the vehicle coasts to apogee, at which time a circularization burn is accomplished.

The Mach no. and altitude combinations during a synergistic maneuver are covered by the ascent-descent flight corridor shown in Figure 2.2-5.

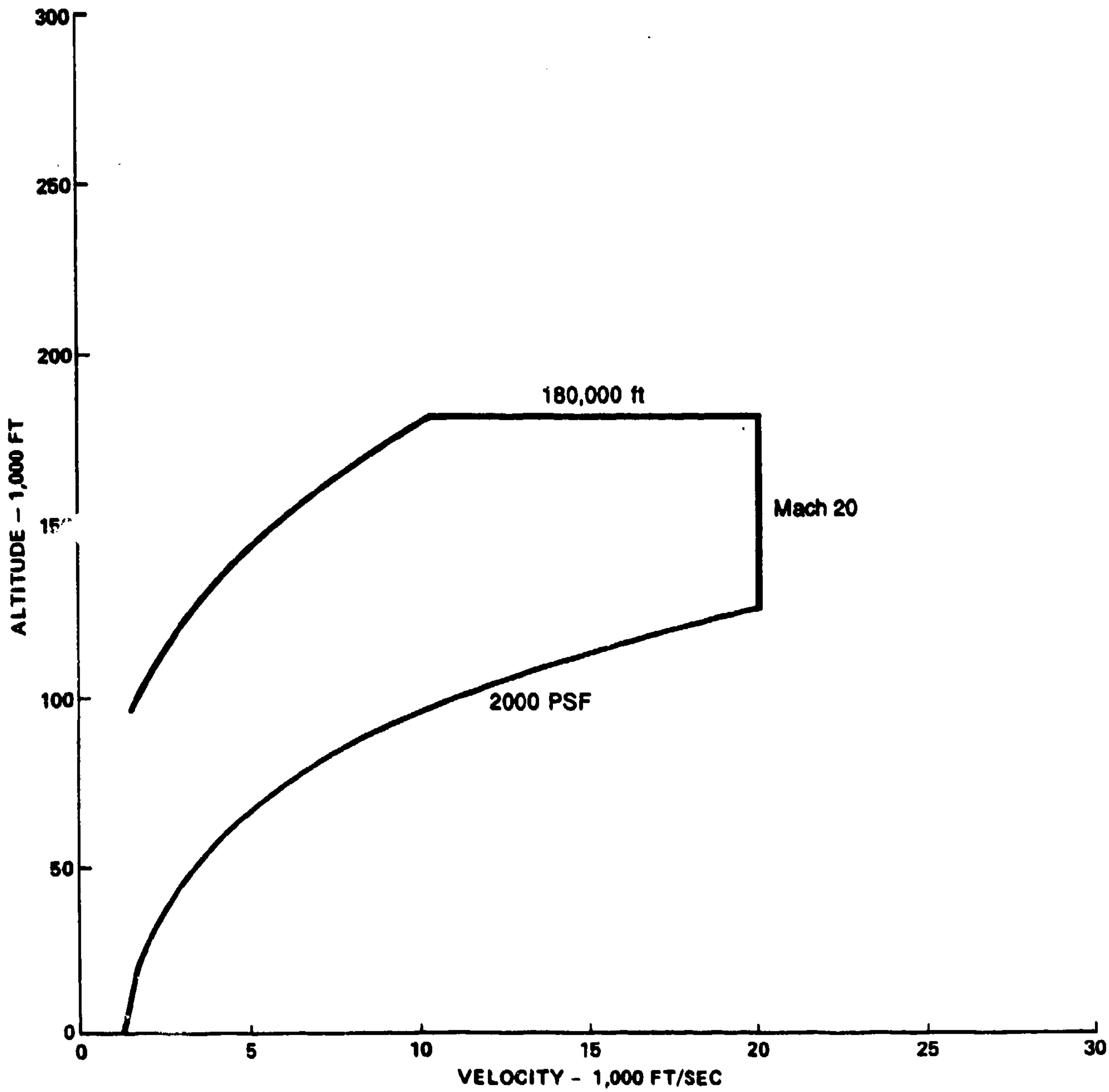


Figure 2.2-6. Atmospheric Mission Envelope for Horizontally-Launched HVT Vehicle

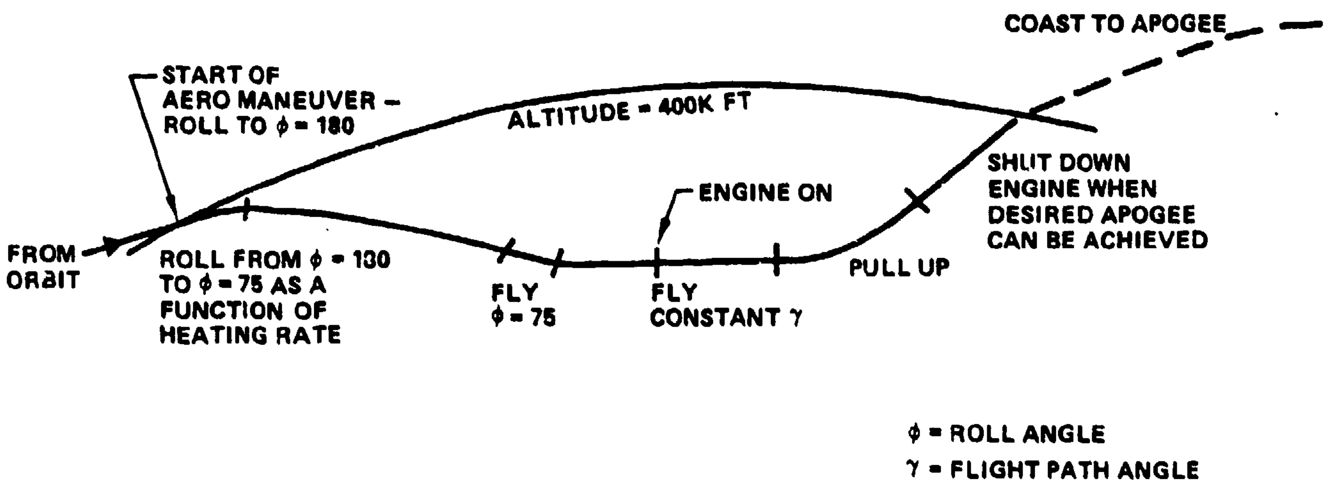


Figure 2.2-7. Typical Synergistic Orbital Plane Change Maneuver

2.2.2 Flight Profiles For Vertically Launched Vehicle

2.2.2.1 Ascent and Descent Profiles

The vertically launched vehicle (VLV) flight profiles do not have much variation between flights. Thus, the typical ascent and descent profiles were used for escape system design.

Typical launch trajectory and sample time histories during ascent for the vertically launched vehicle (VLV) are shown in Figures 2.2-8 and 2.2-9 respectively. Essentially, the vertical launch is followed by a slight pitchover, a gravity turn, and then by a phase which uses pitch to maintain a flight-path angle of 0 deg until the desired velocity is reached (Figure 2.2-8). As can be seen from Figure 2.2-9, the maximum dynamic pressure during the ascent phase is only about 400 psf, occurring at about 40,000 feet altitude and 90 seconds after liftoff. A speed of Mach 3 is reached at about 80,000 feet and 125 seconds after liftoff. The rest of the ascent phase to 300,000 feet takes only about 150 additional seconds. Therefore, the heat soak period during ascent is significantly less for the VLV compared with the HLV. The maximum heating rate during ascent (not shown in Figure 2.2-9) is less than 50 BTU/(ft^2-sec). The booster is separated at about 220 seconds with a corresponding velocity of about 12000 ft/sec and altitude of 230,000 feet. The maximum longitudinal acceleration during ascent is 3.5 g (Figure 2.2-10).

The atmospheric reentry and descent data for the VLV are shown in Figure 2.2-11. The reentry and descent phases are significantly longer than the ascent phase. Speed is reduced to Mach 3 at 120,000 feet altitude about 45 minutes after the deorbit initiation. The maximum dynamic pressure and heat rate during descent are 100 psf and 75 BTU/ft^2-sec, which are slightly higher than the corresponding values for the HLV.

2.2.2.2 High and Low Altitude Operations

Unlike the horizontally launched vehicle, the vertically launched vehicle does not have any atmospheric flight capability other than gliding back to land. The landing speed is 170 to 250 knots, with a glide path angle of about 3 degrees.

2.2.2.3 Orbital Plane Change Maneuver

Like the HLV, the vertically launched vehicle also is designed to make a synergistic orbital plane change maneuver, combining aeromaneuver with usage of propulsive thrust for plane change. The Mach no. and altitude combinations during this maneuver are essentially the same as during the ascent and the descent maneuvers.

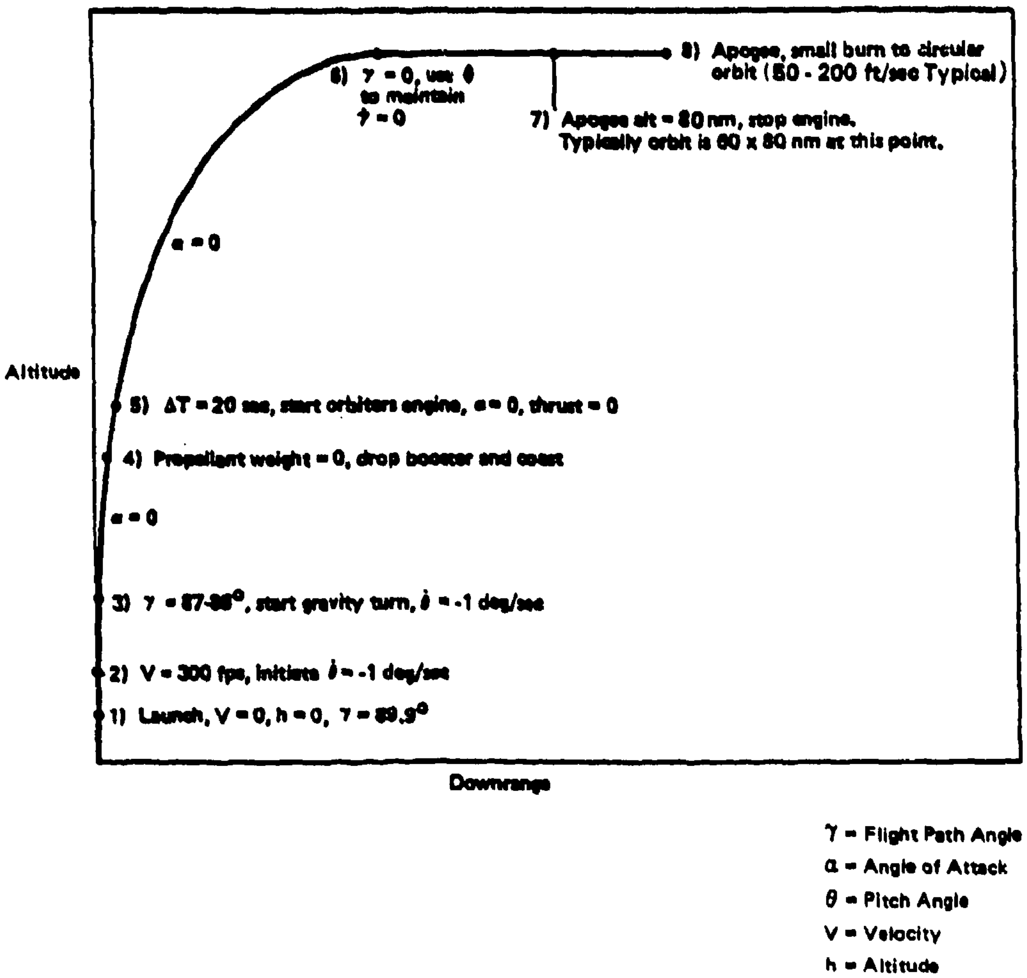


Figure 2.2-8. Typical Launch Trajectory for Vertically-Launched Vehicle

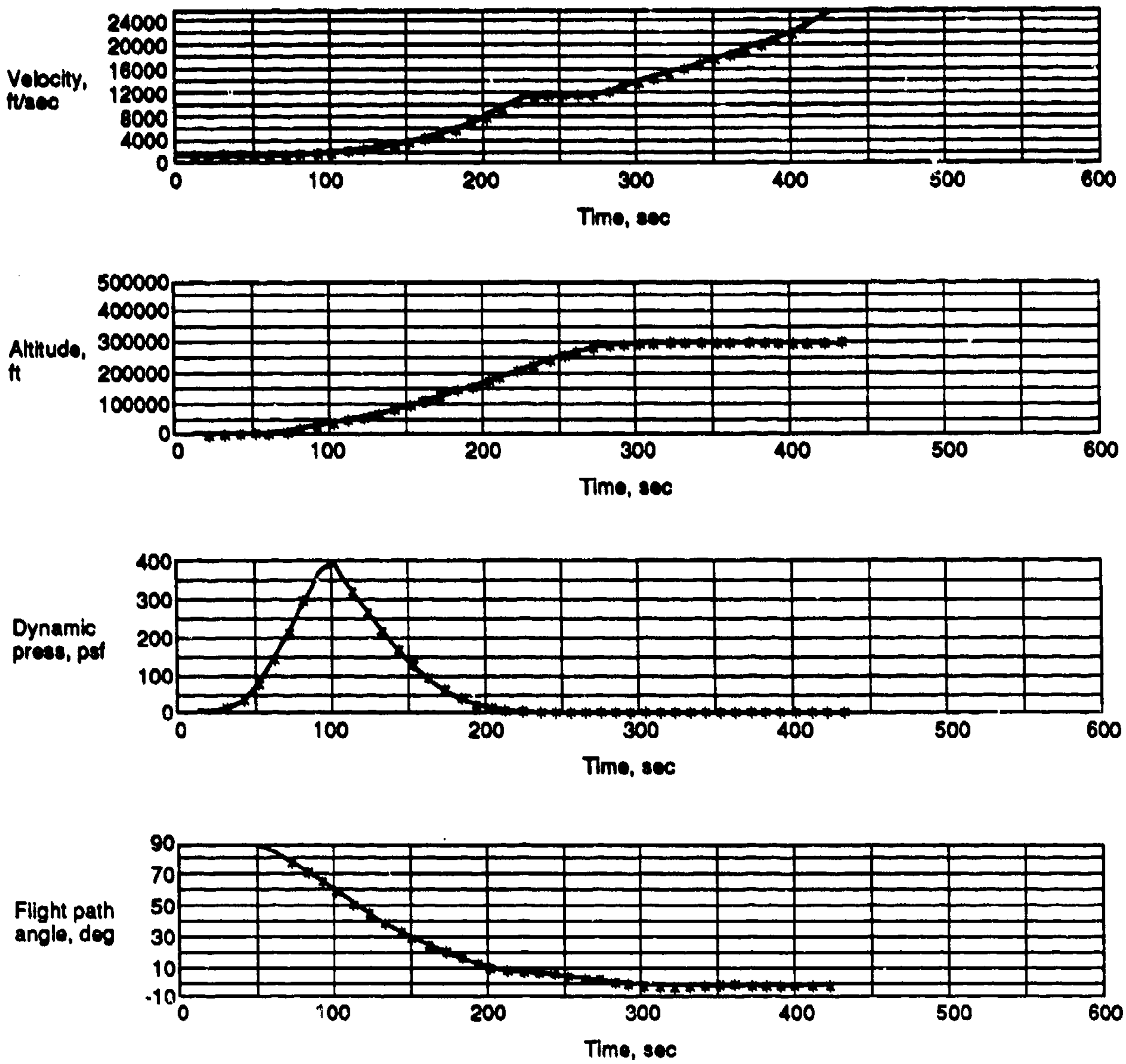


Figure 2.2-9. Typical Ascent Profile Data for the Vertically-Launched Vehicle

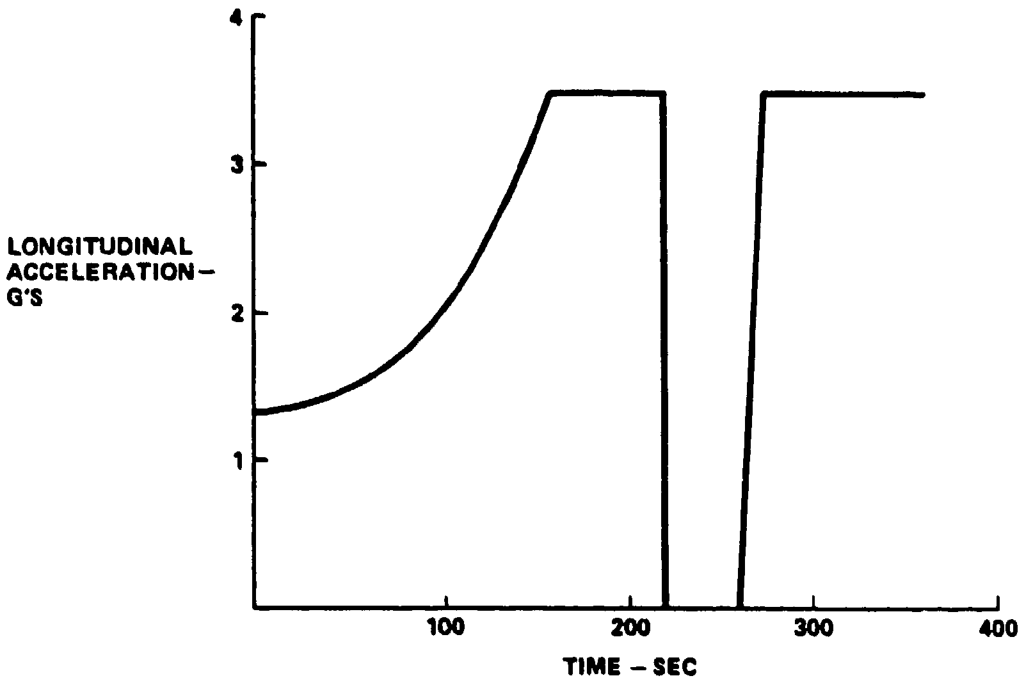


Figure 2.2-10. Longitudinal Acceleration During Typical Ascent for a Vertically-Launched Vehicle

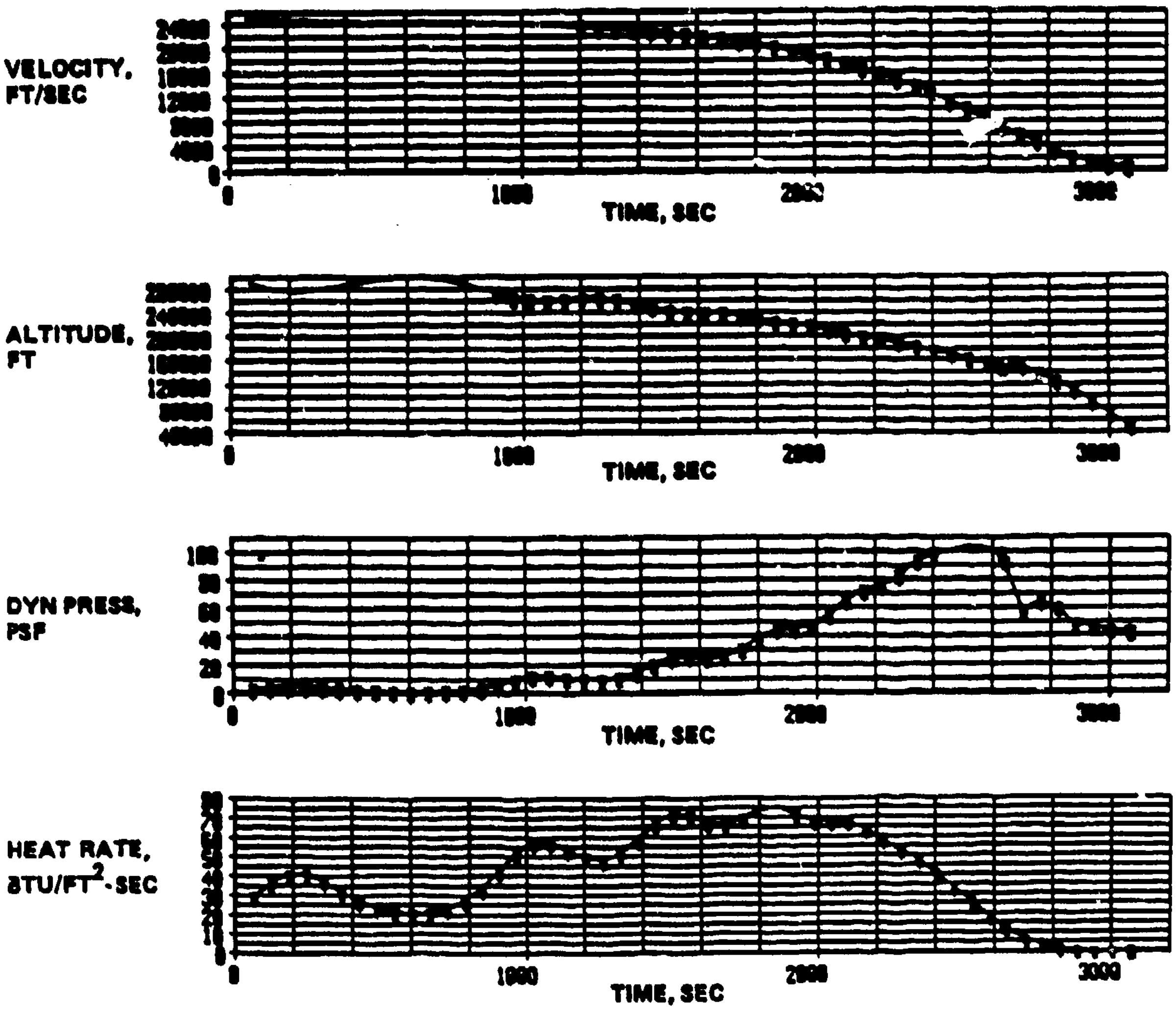


Figure 2.2-11. Typical Atmospheric Reentry Data for the Vertically-Launched Vehicle

2.3 SUBSYSTEM HAZARD ANALYSIS

The nature and the probability of the hazards associated with the HLV and VLV are somewhat different from each other because of the inherent differences in the two vehicles. For example, in case of a HLV, tires could blow during takeoff run, which may require emergency escape from the vehicle. This cannot happen for VLV because it does not have a takeoff roll. On the other hand, the booster propellant explosion can occur for the VLV, but not for the HLV, because the latter does not have a booster.

A subsystem hazard analysis was, therefore, conducted to examine various vehicle systems and their failures, and establish the corresponding emergency escape time requirements. These escape time requirements are given in Tables 2.3-1 and 2.3-2 respectively.

It should be noted that the impact of any given failure depends upon the flight phase as well as the location of the vehicle above the ground. For example, loss of vehicle propulsive power requires immediate ejection close to the ground, but not at high altitudes. Also, different failures within a given system may impose different requirements on the escape system design, depending upon what the corresponding impacts on vehicle performance and safety are.

The number of hazardous events to be analysed for escape system design decreases tremendously, if a slightly different approach is taken. In this approach, one postulates the emergency situations such as explosion, fire, out-of-control vehicle, which will necessitate escape in different flight conditions. The potential causes of these hazardous events are then identified. If these potential causes are probable and need to be designed against, then the escape requirements for these hazardous events are identified. Using this approach, the impact of vehicle operational differences on the escape system design becomes relatively small. For example, if an out-of-control vehicle requires emergency escape within 1 to 10 seconds depending upon the altitude above ground, then it is immaterial, if the vehicle is out of control because of a control system failure or a failed aerodynamic surface. Therefore, the calculation of the probabilities of individual failures becomes unimportant.

The major identified emergencies are:

- Explosion
- Fire
- Out-of-control vehicle
- Damaged vehicle
- Benign system failure
- Hazardous environment

Table 2.3-1. *Escape Time Available For Horizontally Launched Vehicle*

Flight phases	Launch and subsonic and supersonic		Hypersonic atmospheric ascent		Orbital flight and deorbit		Re-entry and synergistic phase		Approach and landing	
Hazard condition / Available time	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Propulsion system: Scramjet; fuel lines, pumps, valves, tanks	<1 S	30 S	1 S	5 M		12 H	5 S	10 S	5 S	10 S
Thermal protection system: Active cooling system insulation and ETS			1 S	5 M		12 H	5 S	5 M		
Life support. Pressurization system oxygen supply contamination		12 H	10 S	12 H	10 S	12 H	10 S	12 H		12 H
Structural failure aerodynamic loading thermal stress	1 S	1 M	1 S	5 M			5 S	10 S		
Avionics and aerodynamic devices	1 S	1 M	1 S	5 M				1 M	1 S	30 S
Collision					10 S	12 H				
Attack					10 S	12 H	10 S	1 M		
Chemical explosion	< 1 S	30 S	< 1 S	30 S	10 S	12 H	10 S	1 M		
Fire	5 S	30 S	5 S	30 S	5 S	30 S	5 S	30 S	5 S	30 S
Landing gear	1 S	10 S							1 S	10 S
Attitude control system			1 S	5 M	5 M	12 H	1 S	1 M		

S = Second
M = Minute
H = Hour

Table 2.3-2. Escape Time Available For Vertically Launched Vehicle

Flight phases	Launch and subsonic and supersonic		Hypersonic atmospheric ascent		Orbital flight and deorbit		Re-entry and synergistic phase		Approach and landing	
Hazard condition / Available time	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Ground equipment										
Sequencing errors	< 1 S									
Disconnect and hold										
Power failure (electrical)										
Propulsion system										
Booster rocket engine	< 1 S	30 S	30 S	1 M						
Orbiter rocket engine			1 M	5 M		12 H	5 S	10 S		
Fuel lines, valves, pumps, tanks	< 1 S	30 S				12 H	5 S	10 S		
Thermal protection system										
Insulation						12 H	5 S	10 S		
ECS										
Life support system										
Pressurization				10 S		10 S		10 S		10 S
Oxygen supply		12 H		12 H		12 H		12 H		12 H
Contamination		12 H		12 H		12 H		12 H		12 H
Structural										
Aerodynamic load	10 S	30 S	1 S	10 M			5 S	10 S		
Thermal stress							5 S	10 S		
Staging disconnects			1 S	10 M						
Aerodynamic devices								1 M	1 S	30 S
Collision					10 S	12 H				
Attack					10 S	12 H	10 S	1 M		
Chemical explosion (fuel)	< 1 S	30 S	< 1 S	30 S	10 S	12 H	10 S	1 M		
Fire (cabin)	5 S	30 S	5 S	30 S	5 S	30 S	5 S	30 S	5 S	30 S
RCS and OMS			1 M	10 M	5 M	12 H		1 M		
Landing gear									< 1 S	10 S

S = Second, M = Minute, H = Hour

Some possible causes for these emergencies, the corresponding time available for escape, and additional considerations are identified in Tables 2.3-3 and 2.3-4. Table 2.3-3 identifies the emergencies and their implication during takeoff/launch, approach, landing, and atmospheric flight. Table 2.3-4 provides similar information for emergency situations during orbital flight.

Table 2.3-3. Major Emergency Situations Requiring Escape During Takeoff/Launch, Approach, Landing and Atmospheric Flight

Emergency	Some possible causes	Time available for escape	Comments
Explosion	• Propellant detonation	< 1 sec. after explosion	More time may be available, if explosion can be predicted by appropriate sensor location. Distance to get away from explosion is also important.
Fire	• Flammable fluids/materials	5 - 30 sec.	Depends upon location and intensity of fire.
Out-of-control vehicle	• Control system failure • Reaction control system failure • Landing gear failure • Collision • Structural failure • Aerodynamic device failure	1 - 10 sec.	Depends upon altitude and rate of departure from controlled flight.
Damaged vehicle	• Collision	1 - 30 + sec.	
Benign system failure	• Loss of engine power • Instrument failure	30 + sec.	
Hazardous environment	• Toxic gas generation • Environmental control failure	1 sec - hrs.	Depends upon type and size of backup life support system.

Table 2.3-4. Major Situations Requiring Escape During Orbital Flight

Emergency	Some possible causes	Time available for escape
Explosion	Propellant detonation	1 second
Fire	Flammable fluids/materials	5 - 20 seconds
Out-of-control vehicle	Control system failure	5 - 10 minutes
Damaged vehicle	Collision with meteroids, debris	1 second to minutes
Benign system failure	Loss of propulsion capability, instruments failure	Hours
Hazardous environment	Environment control failure, toxic gas generation	1 second to hours, dependent upon size of backup life support

3.0 CREW ESCAPE AND PROTECTION REQUIREMENTS

The crew escape and protection requirements used for the design and evaluation of HVT escape system concepts are discussed in this section. Many of these requirements are defined in the SOW, applicable military specifications such as MIL-S-9479B (Reference 8) or MIL-C-25969B (Reference 9), and the Air Force Systems Command Design Handbook 1-3, Human Factors Engineering (Reference 10). These requirements have been tailored for use on HVT escape system design. Selection of other requirements has been made on the basis of other available data.

The crew escape requirements are discussed in Section 3.1 and the crew protection requirements are discussed in Section 3.2.

3.1 CREW ESCAPE REQUIREMENTS

3.1.1 Maximum Mach No., Dynamic Pressure and Altitude Envelope

The crew escape system should provide successful emergency escape over the vehicle flight envelope. The flight envelopes for the HLV and the VLV vehicles are shown in Figure 3.1-1. The vehicles may be in orbital flight up to 300 mi.

It may be noted from Figure 3.1-1 that the maximum dynamic pressure for the HLV is 2000 psf, while that for the VLV is 400 psf. These dynamic pressures are within the range of current capsule and ejection seat designs, as indicated in Figure 1.1-1. The main concern is the required capability to successfully escape at speeds up to Mach 25, compared with Mach 3 capability of current capsules and ejection seats. The major impact of this higher Mach no. will be in the higher temperatures, which the capsule structure or the seat structure and crew member clothing/helmet will experience, and must be designed for.

The higher operating altitude of the HVT vehicles results in the crew life support systems being designed to provide oxygen, pressurization and temperature control for a much longer period, as it will take a longer time for the capsule/crewmember to descend to 15,000 feet or less where recovery parachutes can be deployed.

3.1.2 Low Altitude Performance

The low altitude performance requirements for escape capsules in MIL-C-25969B (Reference 9) are listed in Table 3.1-1. These requirements are essentially the same as required for ejection seats in MIL-S-9479B (Reference 8). However, these requirements

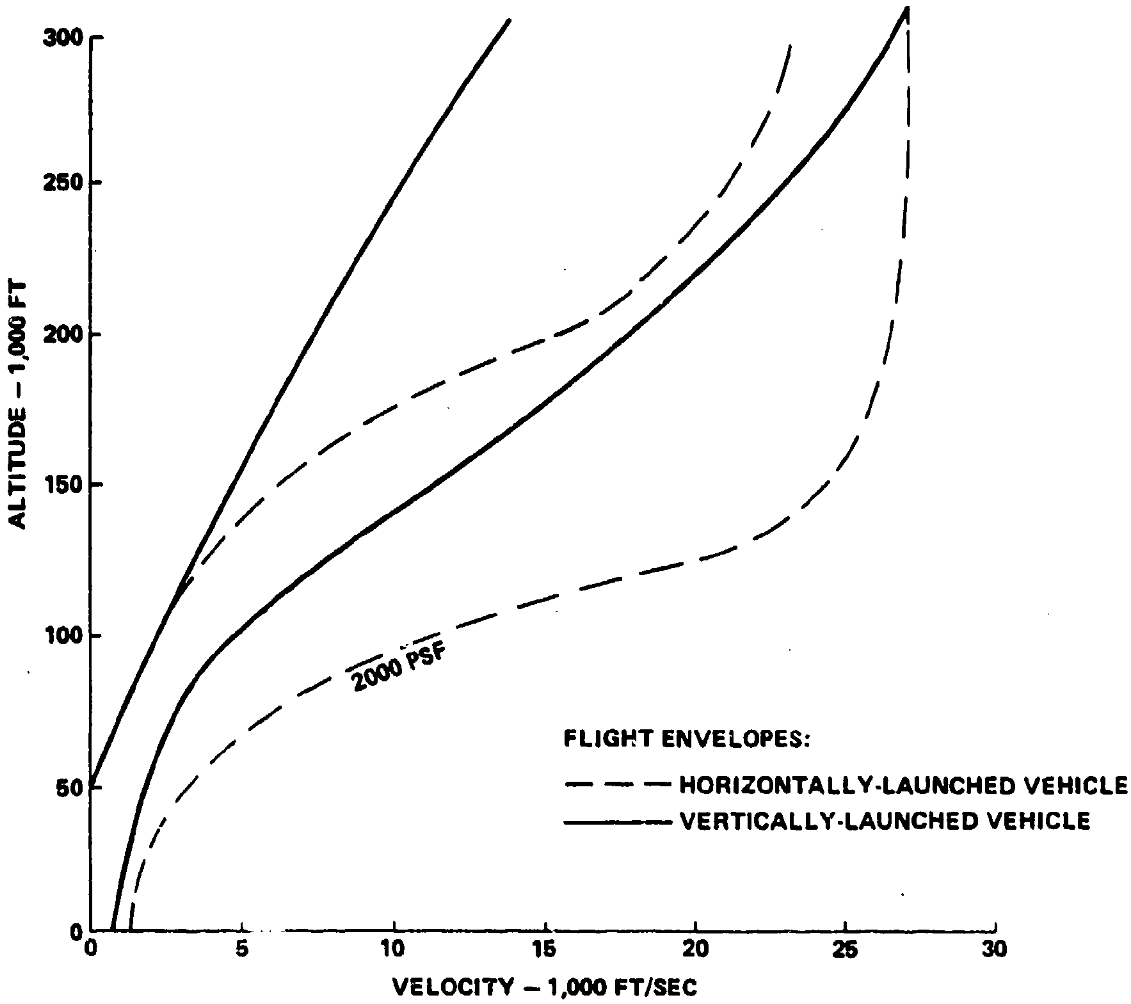


Figure 3.1-1. Flight Envelopes for Horizontally-and Vertically-Launched Vehicles

Table 3.1-1. Low Level Escape Performance Requirements In MIL-C-25969

Attitude		Velocity (knots)	Altitude required (feet)
0° dive	0° roll	0	0
0° dive	60° roll	120	0
0° dive	180° roll	150	200
0° pitch and 10,000 fpm sink rate	0° roll	150	200
60° dive	0° roll	200	500
45° dive	180° roll	250	600
30° dive	0° roll	450	700

should not be applied unchanged for the HVT vehicle crew escape system for the following reasons:

- o Flight missions for the two HVT vehicles do not include sustained low altitude maneuvers close to the ground.
- o The minimum landing speed is 200 knots for the HLV and 170 knots for the VLV.
- o The pitch angle for the VLV is 90 degree (and not zero degree at takeoff).
- o Unnecessarily stringent low altitude performance requirements may make the HVT escape system impractical due to unnecessarily high associated propulsion subsystem size and weight.

Table 3.1-2 shows the low level escape performance requirements used for hypervelocity vehicle escape systems. The first condition is the same as in MIL-C-25969 and applies to escape from vehicles standing still at ground. It applies to HVV only prior to takeoff and to both vehicles after landing. The second condition is a modification of condition 1 for application to VLV prior to takeoff, and does not apply to HLV. The third condition allows some departure from the designed glide path angle of 3 to 5 degree at level wing, without making it unnecessarily stringent.

3.1.3 Range Requirements

The HVT Escape System Concepts SOW (Reference 7) imposed the following requirements on the range of the escape system:

a. The escape system shall allow for recovery within the continental United States (CONUS) for escape initiated from orbit.

b. The escape system shall allow for extended cross range flight for escape initiated during upper atmospheric hypervelocity flight.

c. The escape system shall allow for immediate recovery anywhere on earth for all other flight conditions.

For the purpose of meeting the range requirement "a" stated above, it was assumed that the orbital flight, if extended, will bring the vehicle over the continental United States. This is true for the planned missions of the two vehicles being considered for this study.

The extended cross range capability for escape initiated during upper atmospheric hypervelocity flight is a very desirable feature to have. This cross range capability can be provided by appropriate aerodynamic surfaces providing a good lift/drag ratio or by

Table 3.1-2. Low Level Escape Performance Requirements For Hypervelocity Vehicle Escape System

Cond. no.	Pitch angle, deg	Roll angle, deg	Flight path angle, deg	Velocity, knots	Altitude required, feet
1	0	0	0	0	0
2*	90	0	90	0	0
3	-10	180	-10	250	600

* Applicable to vertically–launched vehicle only. Not applicable to horizontally–launched vehicle.

appropriate propulsion system. Either of the two choices can be expected to increase the escape system weight and complexity. Thus, instead of specifying a rigid value (or values, which vary with escape conditions) for the minimum crossrange capability, it was considered more appropriate to use the crossrange as one of the desirable performance parameters.

3.1.4 Explosive Hazard Design Requirements

An HVT escape system should provide the capability to get the crewmembers to a safe area in case of an explosion at launch or just before launch.

The main dangers due to explosion are:

- shock wave, peak and duration
- thermal radiation
- shrapnel
- fireball

The distances by which the crewmembers must be moved away from the explosion to avoid ear/lung damage due to shock wave, thermal radiation, shrapnel and fireball are shown in Figure 3.1-2 (Reference 10). These distances are a function of the TNT equivalent of the explosive.

The magnitude of the danger to crewmembers depends upon the warning time available before the explosion occurs, the performance of the escape system and whether it is enclosed. For the purpose of this program, instead of establishing the warning time before explosion in advance for the two vehicles during launch, the capability of the different escape systems during such emergency conditions were used as a design criterion during the trade study phase.

3.1.5 Time Available for Escape

The time available for escape during various flight phases depends upon the nature of the emergency situations, as discussed in Section 2.3 and illustrated in Tables 2.3-3 and 2.3-4. These available time values were used as the maximum allowable times for escape.

3.2 CREW PROTECTION REQUIREMENTS

Appropriate crew protection requirements must be satisfied by the designed escape systems to ensure no or minimal injuries to the crewmembers. These include limits on

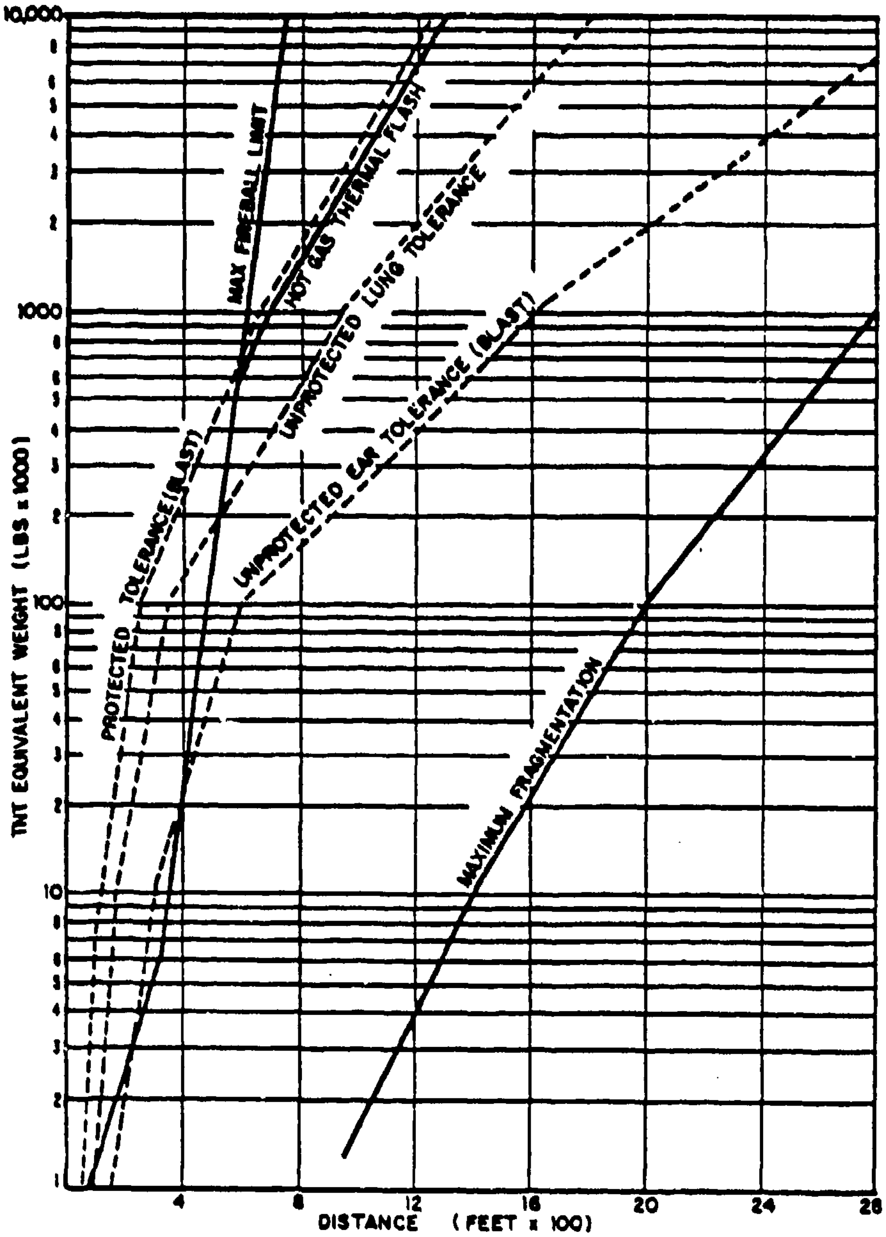


Figure 3.1-2. Estimated Safe Distance from Explosions

accelerations, angular rates, total pressure and oxygen partial pressure, carbon dioxide, environmental temperature, ionizing radiation, windblast and exposure to shock waves. These also include provisions for flashblindness protection, space motion sickness and waste management.

Crew protection requirements are driven primarily by the physiological limitations imposed on the systems by Man. The matrix in Table 3.2-1 summarizes some of the physiological topics which have significant impacts on the design requirements of a hypervelocity escape system.

The escape system requirements discussed below are based on the currently available physiological data. Since the human being doesn't function like a mass produced machine, "requirements" for humans are best given as ranges of value or with mean values and standard deviations. However, single quantities are easier to use for design and have been stated in this section.

3.2.1 Acceleration and Angular Rate Requirements

The physiological effects of high acceleration and angular rates depend upon their duration. Their limits are, therefore, dependant upon whether these are short term or long term.

Short term or impact accelerations can be defined to be those which do not result in a significant steady-state component in the mechanical response of the accelerated body. The injuries are primarily due to the limited load carrying capability of the human body. The short-term accelerations and angular rates are typically experienced during ejection, rocket firing, parachute deployment and ground impact or landings. The short term acceleration and angular rate requirements to be used for the HVT escape system design are as stated in the SOW (Reference 1). By defining the required acceleration limits at a Critical Point close to the chest level, the effect of angular accelerations has been included in these requirements. These requirements are restated in Appendix A for ease of reference.

Accelerations longer than 1 second in duration are usually considered as long term, and the corresponding limits are less then those for short term accelerations. Long term acceleration may be encountered during reentry of the escape system from orbit into upper atmosphere. The physiological effect of these forces is more on the soft tissues and liquid components of the body than on the skeletal system. Sustained $+G_z$ will tend to force blood from the head and upper parts of the body to the lower parts with the corresponding effects of lower blood pressure, and hence oxygen perfusion, to the brain

Table 3.2-1. Physiological Drivers For Hypervelocity Escape System Design

Physiological concern	Physiological symptoms	Impact to hypervelocity escape system design requirements
Acceleration stress • Impact • Sustained	• Musculo-skeletal injury/compression fractures to vertebrae • Fatigue • Grayout • Blackout • Unconsciousness	• Limit to ejection forces which may be applied • Restraint system design considerations • Anti-g suit • Contoured seat cushion • Seat cushion fabrication material • Optimized body position for ejection/seat back angle • Anti-g valves
Decompression • Ebullism • Hypoxia • DCS • O_2 toxicity	• Pain in body cavities • Altitude sickness/ unconsciousness • Bends/chokes/staggers • Boiling of blood and fluids • Respiratory distress/irritation • CNS effects	• Pressurization schedules for HVT and escape capsule • Prebreathe provisions to prevent DCS • Pressure suit internal pressure • Oxygen delivery system design • Fire/explosion safety • Two-gas respiratory system
CO_2 build-up	• Faster respiration • Increased minute volume • Faster heart rate • Acidosis	• CO_2 scrubbers in ECLSS • Oxygen system in HVT and escape capsule
Thermal stress	• Metabolic rate/core temperature increase • Sweat rate increases • Cardiovascular changes • Surface burns/discomfort	• Liquid cooled garments • Ventilation garments • Fire retardant overgarments • Re-entry heat ablation shield • Cooling subsystem in escape capsule
Radiation	• Life-shortening • Carcinogenesis • Tissue damage • Nausea	• Shielding afforded by escape system structure • Individual radiation protection • Dosimetry
Blast noise shock	• Lung damage • Eardrum rupture • Auditory changes (TTS; PTS) • Limb flail • Non-auditory changes (gag, dec. visual acuity) • Reduced psycho-motor performance	• Selection of pressurization schedule deltas • Helmet/ear protection design • Shock attenuator design • Restraint system design
Flashblindness	• Temporary visual disturbance • Chorio-retinal burns	• Wind-screen/helmet visor design considerations • PLZT goggle material
Space motion sickness (SMS)	• Nausea/vomiting • Decreased performance/vigilance • Stomach awareness	• Reduced human operator performance • Vomitus containment provisions • Prophylactic medicines/therapeutic drugs

Key:

HVT = Hypervelocity vehicle
DCS = Decompression sickness
CNS = Central nervous system
ECLSS = Environmental control and life support system
SAA = South Atlantic Anomaly of van Allen radiation belts
TTS = Temporary threshold shift (re: audition)
PTS = Permanent threshold shift
PLZT = Plumblum Lanthanum Zirconate Titanate ceramic wafers
SMS = Space motion sickness

and eyes. This will cause, after time, symptoms familiar to military fighter pilots such as "gray-out", then "black-out" and possibly unconsciousness due to pooling of blood in the lower extremities. These types of G_z forces are combated by devices such as anti-G suits, individually-performed maneuvers such as the M-1 or L-1, and other factors such as specific pre-conditioning (weight training) and environmental conditions.

Too high values of sustained $-G_z$ acceleration may cause headache, lacrimation, and "red-out". Similarly, too high values of sustained $+G_x$ may cause relative bradycardia, visual loss, dyspnea; and too high values of sustained $-G_x$ acceleration may cause decreased visual activity and chest pain.

The maximum allowable values of sustained acceleration depend upon their duration. These acceleration limits are shown in Figure 3.2-1 (Reference 12).

The sustained angular pitch rates should be maintained in the safe region shown in Figure 3.2-2 (Reference 10). Similar curves for roll rate and yaw rate limits are not available. The sustained roll rate limits were assumed to be the same as pitch rate limits, since the physiological endpoint, cerebral damage, would be the same for rotation about the roll or pitch axis with identical origin. Yaw rates of 90 - 100 rpm have been found tolerable for a few minutes (Reference 11), and were used for HVT escape system design. Higher values of yaw rate can cause severe discomfort because of the hydrostatic gradient that develops along the forearms and thighs.

3.2.2 Total Pressure and Oxygen Partial Pressure Requirements

In order to ensure optimal performance and safety, the pressure and composition of the crewmember ambient atmosphere should:

a. Provide adequate partial pressure of oxygen to prevent oxygen lack (hypoxia);
b. Provide sufficient total pressure to prevent vaporization of body fluids (ebullism);
c. Optimize inert gases in the atmosphere so that if rapid or explosive decompression occurs, decompression sickness symptoms would be minimized or averted;
d. Not pose toxic effects to the human occupant (i.e., oxygen toxicity);
e. Not pose a fire or explosion hazard.

Rapid or explosive decompression, as in loss of cabin pressurization in space (above 50,000 feet MSL), could have fatal consequences (depending upon initial altitude), if the crewmember is not wearing a full pressure suit. Decompression to below 47 mm Hg (0.9 psia) would cause ebullism (boiling of body fluids), because at this "altitude" the

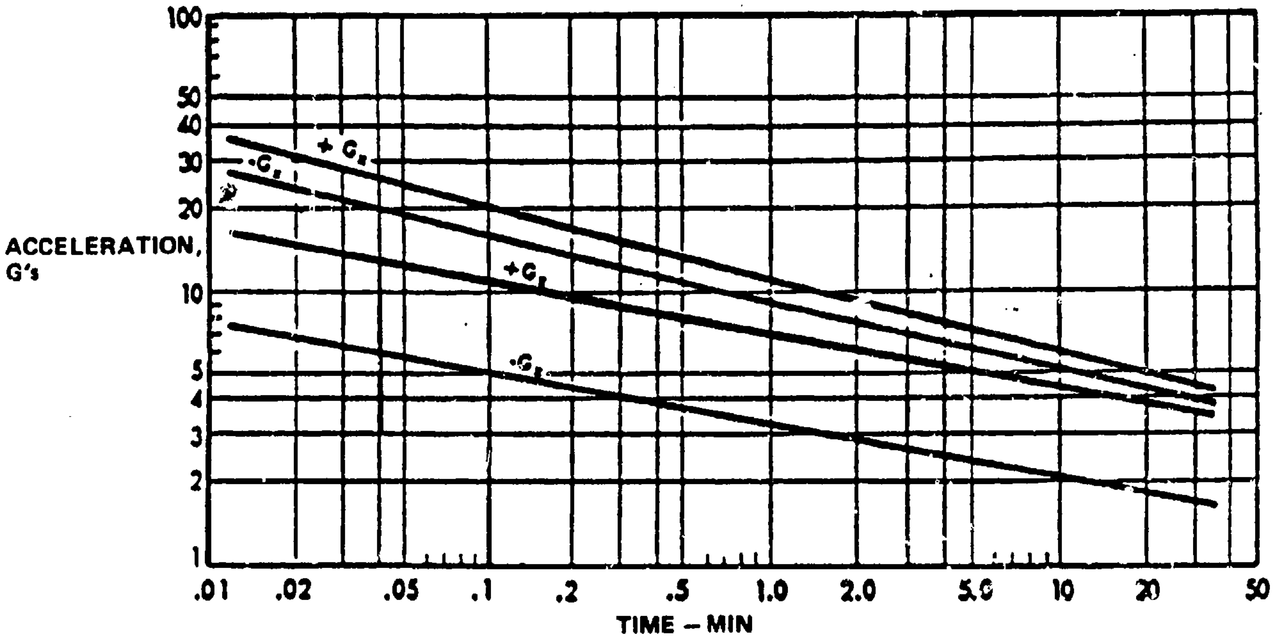


Figure 3.2-1. Linear Acceleration Limits for Unconditioned and Suitably Restrained Crewmember in Upright Sitting Position

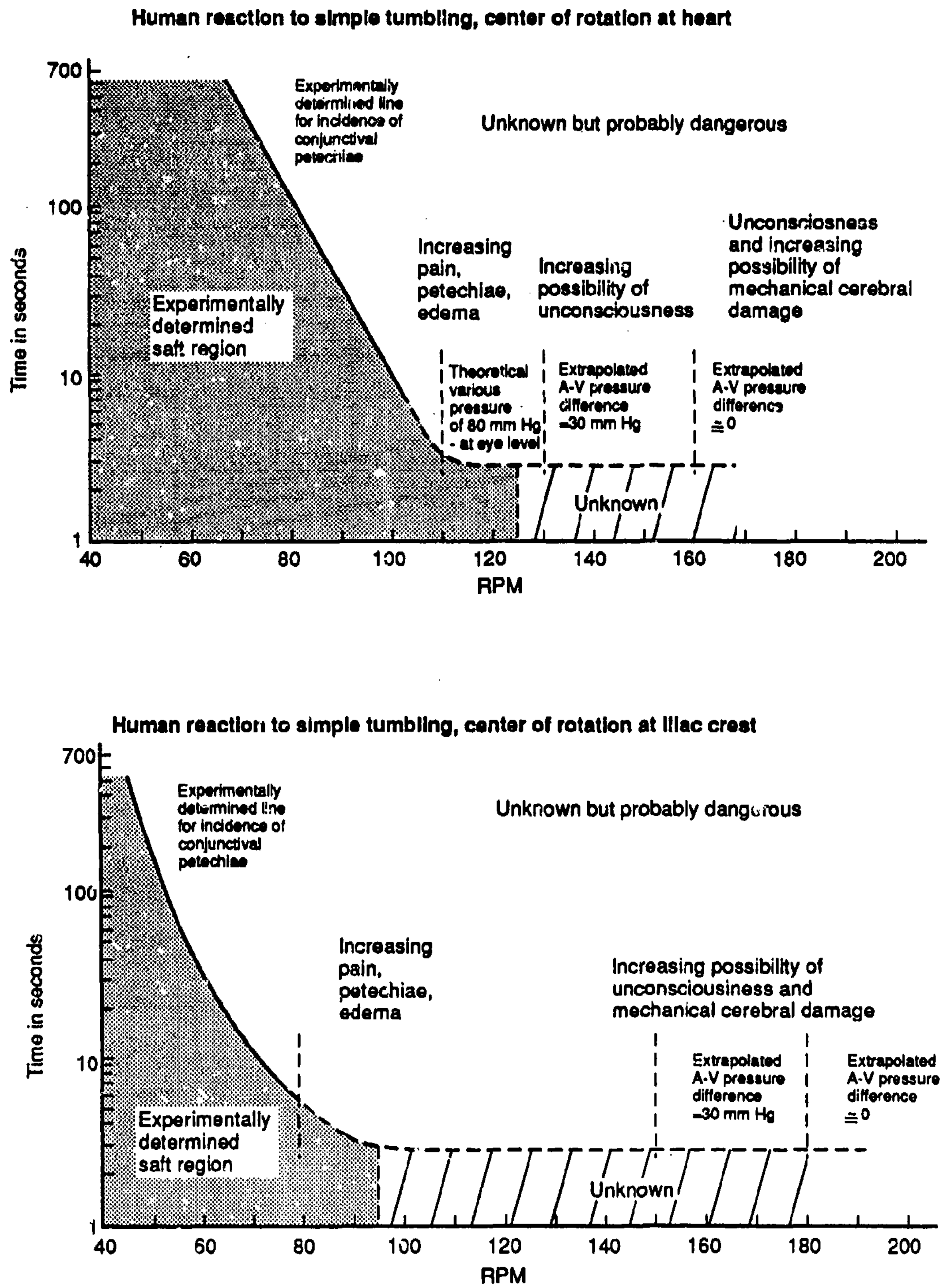


Figure 3.2-2. Angular Rate Limits for Rotation about the Pitch Axis with No Superimposed Deceleration Field

vapor pressure of water in the body exceeds the total pressure. This phenomenon would be rapidly fatal if not defended by a "back-up" pressurization system (i.e., full pressure suit).

Earth's atmosphere contains 21 percent oxygen, 78 percent nitrogen and 1 percent other inert gases. Nitrogen is a physiologically inert gas and people adapted to sea level have over a liter of dissolved nitrogen in their body. When the ambient pressure is reduced, nitrogen bubbles form in the body tissues. If the drop in pressure is not too great or too fast, bubbles evolved in the tissues are safely carried to the lungs by the bloodstream, where the lungs act as gas separators, eliminating evolved N_2 from the body. If, however, the rate and magnitude of pressure change is rapid, the dissolved gases may come out of solution in the form of gas bubbles which may give rise to the signs and symptoms of decompression sickness (DCS) such as "bends", "chokes", "paresthesias" etc. Following decompression, it usually takes several minutes for symptoms to develop. Other factors can influence the rate of development of symptoms such as the individuals' physical activity, age and body fat.

Recent USAF and NASA research indicates that, when considering a 14.7 psia "cabin altitude", the zero incidence of bends requires that pressure suit be at 9.5 psia [Reference 13] for no clinical symptoms and no "bubbling" as detected by ultrasonic technique. The DCS symptoms may not appear until at slightly lower total pressures (8 psia - 9 psia). Since the pressurization system of both the HLV and the VLV have been designed to maintain a pressure of 8 psia, the same total pressure limit of 8 psia was used for "no oxygen prebreathing conditions".

Since decompression sickness is correlated with the amount of nitrogen in the body, one way to decrease the DCS incidence at lower ambient pressure is to eliminate nitrogen from the body. This may be done by breathing 100 percent oxygen (denitrogenation) for at least 1 hour prior to exposure to low barometric pressures.

The minimum acceptable total pressure breathing 100 percent oxygen is 187 mm Hg (3.6 psia). This value is based on the fact that 47 mm Hg is exerted by water vapor, 40 mm Hg by CO_2 produced by the body and the remaining 100 mm Hg is due to oxygen. Under these conditions, the body would receive essentially the same partial pressure of oxygen as breathing air (21 percent O_2; 78 percent N_2), at sea level.

If less than 100 percent oxygen concentration is used, then the minimum acceptable partial pressure of oxygen in the inspired gas in the escape vehicle or the pressure suit, as applicable, is still 187 mm Hg or 3.6 psia. The overall desirable percentage of oxygen for unimpared performance is shown in Figure 3.2-3 as a function of total pressure (Reference 10).

Oxygen in high concentrations can be harmful but oxygen toxicity is not expected to be an operational concern in the development of a hypervelocity escape system since the time of exposure to increased partial pressures of oxygen should be short. People who breathe 100 percent O_2 at sea level for 6 - 24 hours complain of substernal distress and exhibit a reduced vital capacity. However, Astronauts who breathed pure oxygen at space suit pressures (3.8 psia) and Apollo spacecraft cabin pressure (5.0 psia) did not experience signs or symptoms of oxygen toxicity [Reference 14]. High partial pressures of oxygen should also be avoided in order to minimize the danger of fire and explosion.

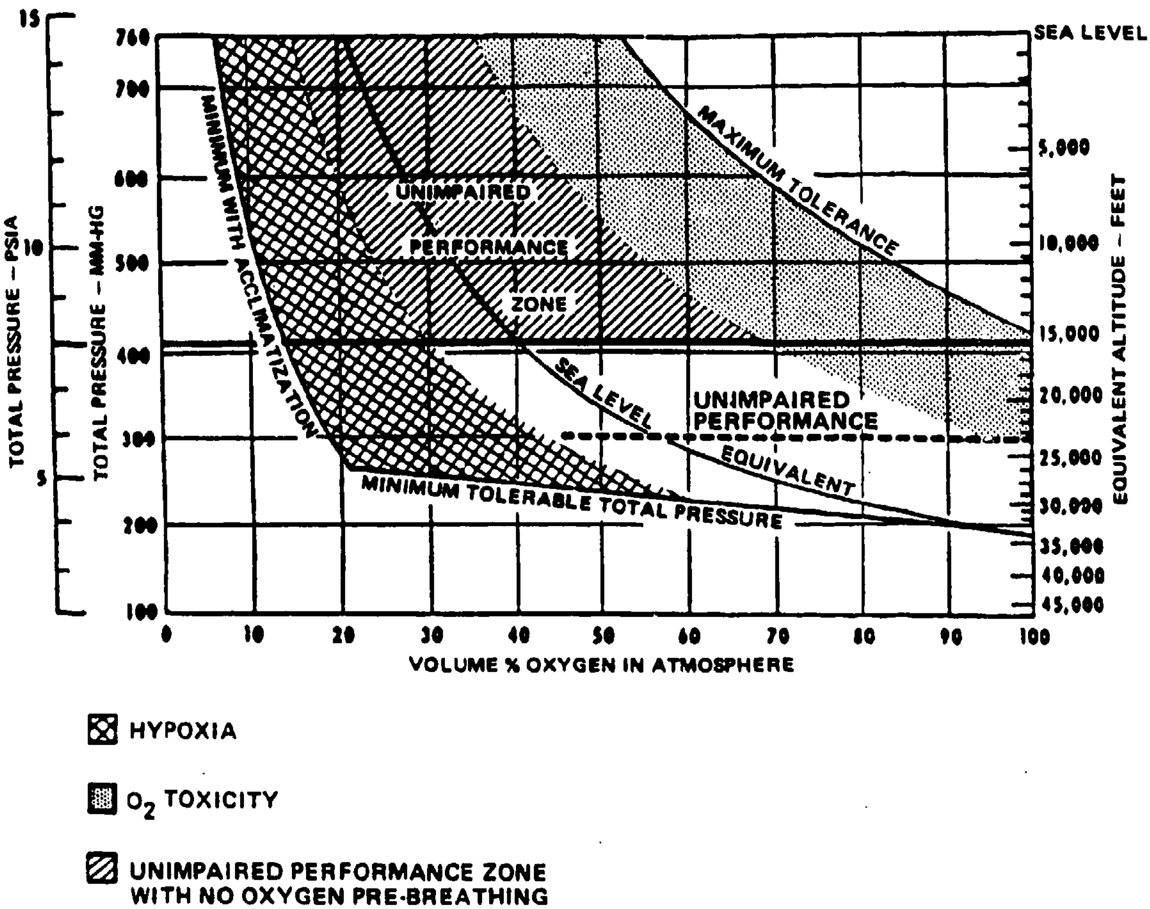
3.2.3 Carbon Dioxide Concentration

Carbon Dioxide, CO_2, is a waste product of Man's metabolism and, therefore, crewmen are the main source of carbon dioxide in the aerospace vehicle's environment. At rest, about 400 liters of CO_2 are produced per person per day. But this figure increases significantly with increases in physical workload. There is no minimum amount of carbon dioxide required in a breathing medium (only 0.03 percent of the Earth's atmosphere is CO_2), but the maximum CO_2 must be limited so as not to stimulate respiration (cause hyperventilation) and heart rate to too great an extent. Also, CO_2 converts to a weak acid (carbonic acid) in the body which lowers the pH (causes acidosis).

NASA's CO_2 limits for closed environments are as follows [Reference 18]:

Indefinite exposure	3.8 mm Hg (torr)
Limited duration mission	7.6 mm Hg
Restricted activity	15.0 mm Hg
Mission abort if correction not possible	15.0 mm Hg

It should be acknowledged that, while not desirable, humans can adapt to remarkably high levels of CO_2 and still function reasonably well. In certain life-threatening situations it might be essential to deal with CO_2 levels higher than 15 mm Hg even though the personnel would not be acclimated to it. The following data show the effect of 10 percent CO_2 (76 mm Hg at sea level) on some body functions.



NOTE: NO OXYGEN PRE-BREATHING REQUIRED
FOR TOTAL PRESSURE GREATER THAN 8 PSIA

Figure 3.2-3. Pressure-Altitude/Oxygen Enve'ope for Long Duration Operations

Inspired Gas	Ventilation (liters/min)	Blood Pressure (mm Hg)	Pulse Rate (beats/min)
Air	27	145/80	96
10% CO_2 in Air	124	200/100	130

The time of exposure to elevated CO_2 is relevant as illustrated in Figure 3.2-4. Some crew discomfort is acceptable during an emergency escape. The upper limit of the "pronounced discomfort zone" in Figure 3.2-4 should be used for HVT escape system design.

3.2.4 Environmental Temperature

Man is a homeotherm; that is, it maintains a constant internal temperature. The body's metabolism produces heat which must be lost to the environment by conduction, convection, radiation, and, most importantly for Man, evaporation of sweat. During emergency escape, thermal imbalances can be caused by inadequate capsule cooling or inadequate pressurized suit thermal control. When the environmental temperature is increased, arterial/venous shunts are opened in the skin increasing blood flow in these areas, which enhances dissipation of heat. Sweating occurs, and via evaporation, augments the radiative and conductive methods for control of body temperature. Prolonged sweating may lead to salt and fluid imbalance, which can result in heat cramps and dehydration. Even if fluid and salt are replaced, the great demands for skin blood flow may encroach on the capacity of the heart to meet the needs for an increased cardiac output if exercise is required. If body temperature continues to rise because of inadequate thermoregulation, heat stroke will occur.

The physiological comfort or stress experienced by a crew member is essentially a function of the skin temperature. For comfort, the mean skin temperature should be maintained at 91°F and the regional skin temperature should not differ from this by more than 6°F. At skin temperature greater than 97°F, fainting may occur. If the temperature inside the skin at a depth of about 0.1 mm beneath the skin surface reaches about 113°F, skin may be damaged and pain experienced.

The above skin temperature limits can be indirectly controlled by maintaining the ambient air and surface temperature within the desired ranges.

Figure 3.2-5 shows the ambient temperature limits as a function of time, at which various physiological effects can be expected to happen [Reference 10]. During

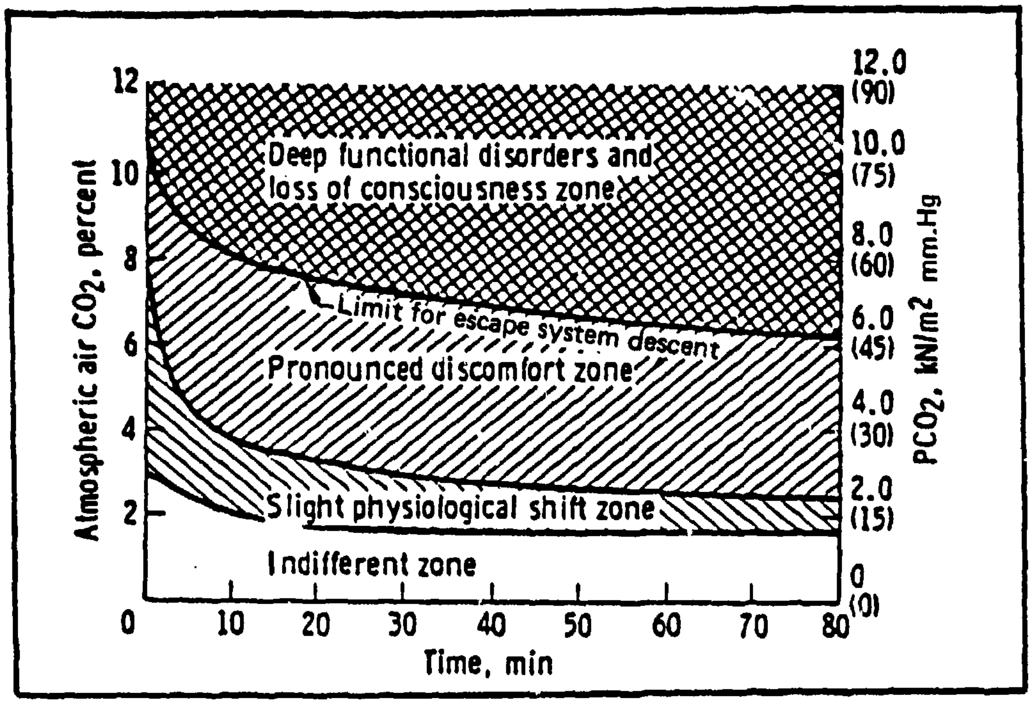
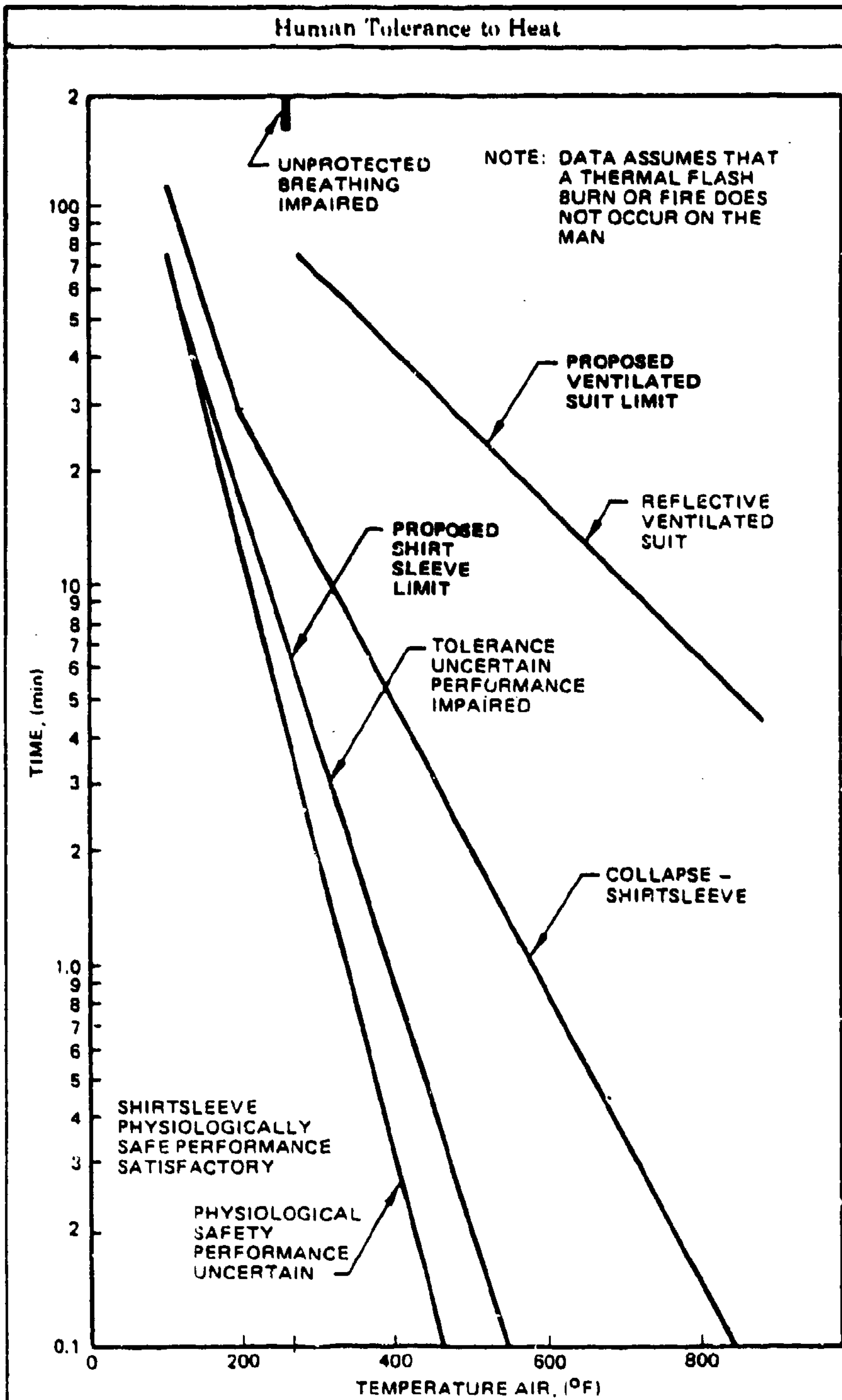


Figure 3.2-4. Physiological Effects of Increasing Carbon Dioxide in an Artificial Gas Atmosphere



Metric equivalents	
°F	°C
200	93.3
400	204.4
600	315.6
800	426.7

Figure 3.2-5. Environmental Temperature Exposure Limits for HVT Vehicle Crew Escape

emergency escape, some discomfort and crew performance degradation is acceptable. Therefore, the proposed shirt sleeve limit during emergency escape is the same as the "tolerance uncertain, performance impaired" curve and the proposed ventilated suit limit is the same as the "reflective ventilated suit" curve in Figure 3.2-5.

The temperatures of the surfaces coming into contact with the crewmember must also be controlled to avoid skin burns. Table 3.2-2 shows the metal surface temperatures and the corresponding surface temperatures, which can be tolerated with different types of gloves. Based upon this, a limiting value of 140°C (300°F) could be used for maximum surface temperature, with the stipulation that the gloves and clothing worn by the crewmembers will provide burn protection equivalent to arctic mittens.

3.2.5 Ionizing Radiation

During emergency escape from low altitude orbital flight, the crewmembers may be exposed to ionizing radiation due to cosmic rays. However, this radiation level is relatively low compared with radiation from the high-energy protons emitted from the sun during sun flares or the Van Allen radiation belts, which will be of concern at altitudes higher than 500 miles or so. Van Allen belts do extend down to about 100 miles altitude at some regions of the earth, especially in the south Atlantic area ("South Atlantic Anomaly"), and if emergency re-entry were envisioned through such regions or during a solar flare cycle, special design precautions would be prudent. However, the exposure levels are small enough to be of little concern during low altitude orbital flight of the HVT vehicle. In any case, based upon the data in Table 3.2-3 (from Reference 11), the maximum dosage level should be kept below 10 rads, at which no effects on the body have been detected.

3.2.6 Windblast Protection

Windblast protection must be provided so that no limb injury occurs due to limb flailing during ejections at high speed. This is not of concern for enclosed escape devices, such as escape capsules or encapsulated seats. For open ejection seats or extraction systems, speeds corresponding to 50 percent injury probability level or advertised maximum speeds, whichever are lower, can be accepted as the limits for adequate windblast protection.

3.2.7 Exposure to Shock, Blast and Impact Sounds

Shock waves due to explosions at vehicle launch may cause injuries to crewmembers due to dynamic pressures exceeding human tolerance. For example, overpressure of 15

Table 3.2-2. Pain From Conductive Heating

Body area	Clothing worn	Metal surface temperature, °F	Average tolerance time, sec
Hand	Bare skin	120	10 to 15
Fingertip	AF/B-3A leather gloves	150	12.6
	AF/B-3A leather gloves	160	7.3
Palm of hand	AF/B-3A leather gloves	150	25.2
	AF/B-3A leather gloves	175	9.7
	AF/B-3A leather gloves	185	8.0
Palm of hand	Aluminized asbestos glove	250	13.5
	Arctic mitten	300	18.7
	Arctic mitten plus B-3A glove	300	37.0
	Arctic mitten plus B-3A glove	400	27.6
	Pigskin 800°F heat glove	300	30.7
	Pigskin 800°F heat glove	400	21.0
	Pigskin 800°F heat glove	500	18.5

Note: Light-touch pressure (less than 1 psi) applied to heated surface.

Table 3.2-3. Expected Short-Term Effects From Acute Whole-Body Radiation

Dose in rads	Probable effect
10 to 50	No obvious effect, except, probably, minor blood changes.
50 to 100	Vomiting and nausea for about 1 day in 5% to 10% of exposed personnel. Fatigue, but no serious disability. Transient reduction in lymphocytes and neutrophils.
100 to 200	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25% to 50% of personnel. No deaths anticipated. A reduction of approximately 50% in lymphocytes and neutrophils will occur.
200 to 350	Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness, e.g., loss of appetite, diarrhea, minor hemorrhage. About 20% deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months, although many have second wave of symptoms at about 3 weeks. Up to 75% reduction in all circulating blood elements.
350 to 550	Vomiting and nausea in most personnel on first day, followed by other symptoms of radiation sickness, e.g., fever, hemorrhage, diarrhea, emaciation. About 50% deaths within 1 month; survivors convalescent for about 6 months.
550 to 750	Vomiting and nausea, or at least nausea, in all personnel within 4 hours from exposure, followed by severe symptoms of radiation sickness, as above. Up to 100% deaths, few survivors convalescent for about 6 months.
1000	Vomiting and nausea in all personnel within 1 to 2 hours. All dead within days.
5000	Incapacitation almost immediately (minutes to hours). All personnel will be fatalities within 1 week.

psia for 0.1 second may cause lung damage and that of 5 psi for 0.1 second may cause rupture of the unprotected eardrum [Reference 15]. Figure 3.2-6 presents the unprotected ear and lung tolerance distance versus the TNT equivalent weight of the blast. These distances are based upon the 15 psi and 5 psi limits mentioned above which reflect recommendations of the CHABA (Committee on Hearing and Bio-Acoustics of the NRC-NAS). These apply to an unprotected crewmember (without ear protection). The protected tolerance distances i.e., tolerance distances for crewmembers in an escape capsule or with properly designed personal equipment are also shown in Figure 3.2-6.

Even if the shock sounds do not rupture eardrums or do lung damage, they can cause auditory effects such as TTS (temporary threshold shift), or even PTS (permanent threshold shift) if permanent damage is done to the organ of Corti of the inner ear. A 180 dB peak impulse results in approximately a 25 dB TTS; a 190 dB impulse in a 50 dB TTS. In addition to direct tissue damage, other non-auditory effects of impulse and blast noise over 150 dB may include reduced visual acuity; gag sensations and respiratory rhythm changes. Figure 3.2-7 presents CHABA damage-risk criteria for impulse noise. The definitions of the A-duration and B-duration times shown in Figure 3.2-7 are as follows:

- A-duration (or the pressure wave duration) is the time required for the pressure to rise to its initial or principal positive peak and return at least momentarily to ambient pressure.
- B-duration (or the pressure envelope duration) is the total time for which the envelope of pressure fluctuations is within 20 dB of the peak pressure level.

3.2.8 Flashblindness Protection

Flashblindness may be of concern in HVT routine and emergency escape situations. Fuelling [Reference 16] states that, "At 10,000 feet, the intensity of light is 12,000 foot-candles (or millilamberts) and in space is about 13,600 ft-c. At these levels light is too intense for comfort. The upper limit of tolerance for normal vision is between 10,000 and 100,000 ft-c (mL),. This would be equivalent to staring at the Sun or at the detonation of a nuclear weapon." Permanent chorio-retinal damage can be done at these light intensities without protection.

The flashblindness apt to be experienced in an HVT would be temporary in most cases but reduces retinal sensitivity and poses a threat to the crewman's ability to operate his vehicle. A standard dark helmet visor affords some protection but for

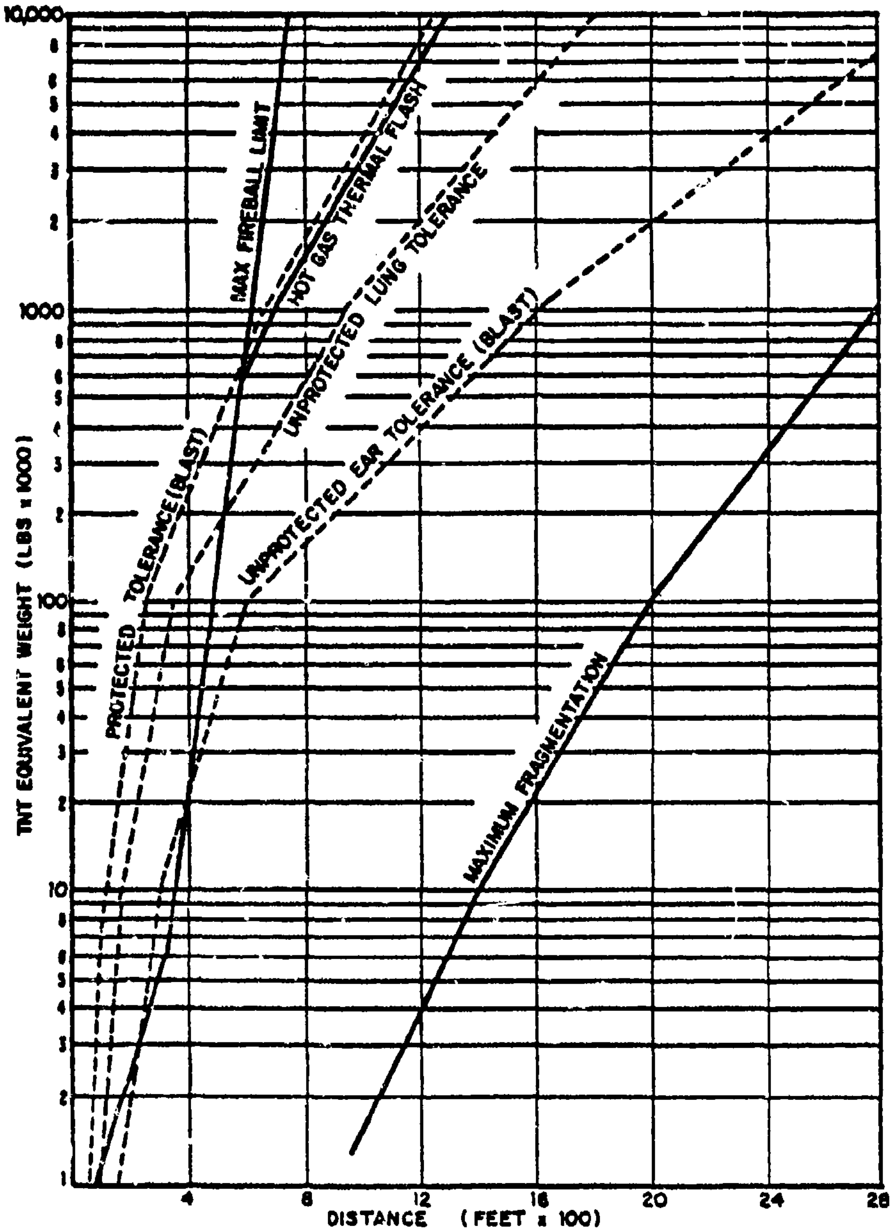


Figure 3.2-C. Estimated Shock and Blast Tolerance Distance

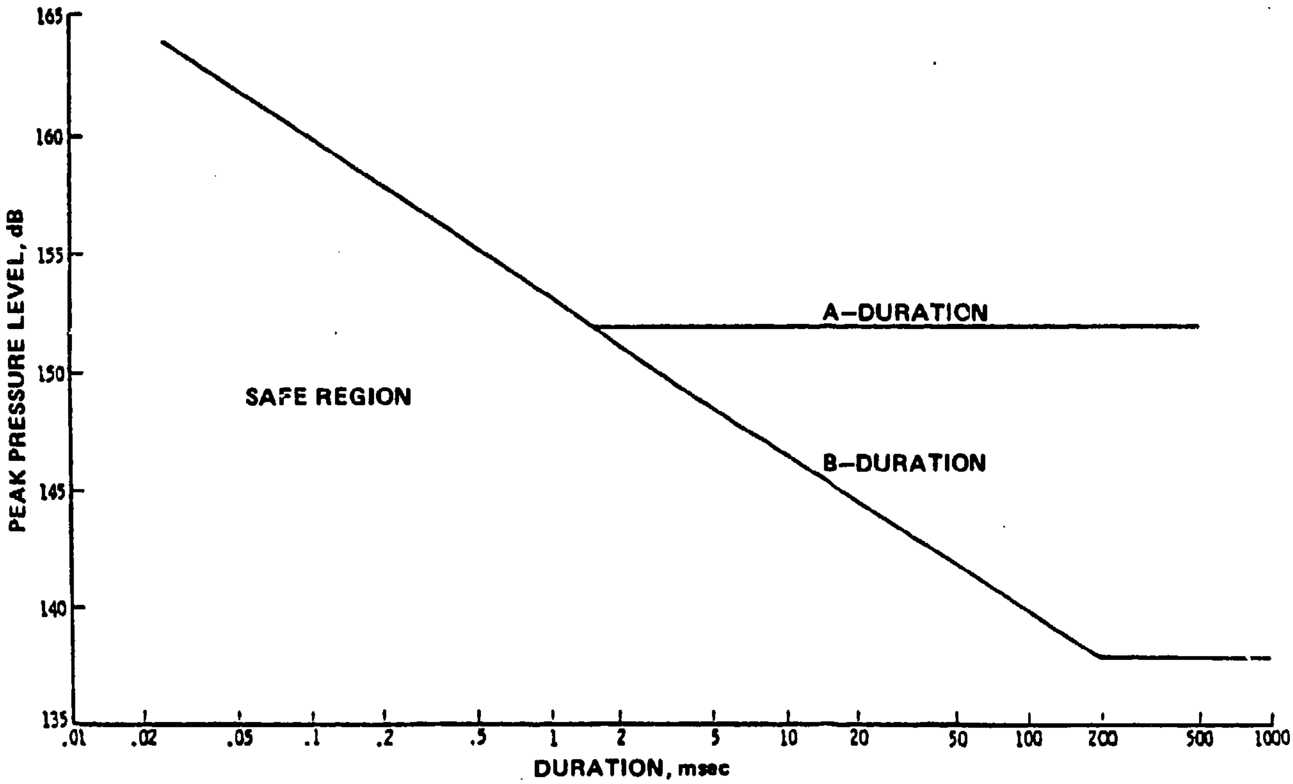


Figure 3.2-7. Damage Risk Criterion for Impulse Noise

extremes cases (such as nuclear explosion), PLZT (transparent plumblum lanthanum zirconate titanate ceramic wafers) material should be used in the goggle.

3.2.9 Space Motion Sickness (SMS)

Since Space Motion Sickness (SMS) has been primarily an operational problem plaguing Astronauts and Cosmonauts of large-volume space vehicles before habituation can take place, it may not be of significant concern for crewmembers of the small HVT vehicle of escape system. On the other hand, crewmembers of this vehicle may not experience orbital spaceflight enough to adapt (habituate) to SMS since NASA experience indicates that this takes about 3 - 4 days. Also, the psychological stress concomitant with the need to abort hypersonic, sub-orbital flight could precipitate symptoms especially since central nervous system entities mediate this disorder.

Space Motion Sickness, as with motion sickness of any variant, has often dramatically deleterious effects on performance. There are several pharmacological agents which, although effective, have undesirable side effects. New approaches such as the use of transdermal scopalamine administration, which is effective for 3 days, may be appropriate for HVT crewmembers for routine and emergency operations. Also, vomitus containment must be considered should SMS occur, especially with a crewman wearing a pressure suit or otherwise restricted [Reference 17].

3.2.10 Waste Management

Waste management will be of concern for a HVT escape during orbital flight. As previously mentioned, the handling of vomit without interference with the respiratory or visual functions of masks/helmets must be assured. Personal equipment should have some capability for urine and feces containment.

4.0 PRELIMINARY ESCAPE CONCEPTS SCREENING

A total of 16 escape system concepts were evaluated for their possible ability to satisfy the crew escape and protection requirements during escape over any part of the HVT vehicle flight envelopes. These concepts are:

a. Extraction system
b. Open ejection seat
c. Encapsulated seat with thermal protection
d. Separable nose capsule with thermal protection
e. Pod-type capsule with thermal protection
f. Inflatable capsule with reentry capability
g. Paracone with reentry capability
h. Mating with orbiting space rescue station
i. Rocket-pack escape to space rescue station
j. Rocket-pack escape to a reentry rescue capsule
k. Mating with rescue vehicle
l. Non-reentry capsule escape to rescue vehicle
m. Ejection seat with orbital rescue
n. Extraction system with orbital rescue
o. Ejection seat with inflatable reentry capsule
p. Ejection seat with rocket-pack transfer to rescue capsule

The salient features of these concepts, as well as their advantages, disadvantages and overall evaluation are discussed in the following subsections. Only concepts numbered c, d, and e above were found to be feasible for all phases of flight, which include: launch, atmospheric flight including that at hypersonic speeds, orbital flight, reentry into the atmosphere, terminal approach and landing. The details of these concepts are developed in more detail for the dual-place HLV and the single-place VLV configurations in Section 5.0.

4.1 CONCEPT 1 - EXTRACTION SYSTEM

An extraction system, such as the UPCO Ranger or Stanley Yankee Escape System has been used for trainer airplanes and is being developed for space shuttle crew escape. The system consists of a tractor extraction rocket, a drogue parachute for directional stability, a standard personnel parachute, a folding seat with the back of the seat remaining with the crew. Extraction systems have been qualified up to 315 KEAS.

When ejection is necessary, actuation of the ejection control jettisons a hatch above the crew and initiates launching of the spin-stabilized extraction rocket. Upon reaching riser line stretch, the extraction rocket is ignited and the crewmember is pulled from the vehicle's cockpit to a height sufficient for safe recovery. The folding seat allows the legs to straighten out, allowing the crewmember to go through a relatively small opening. An integral sensor separates the rocket from the crew member just prior to rocket burnout. A drogue parachute positions the crew member facing the relative wind for optimum recovery parachute deployment. Following the extraction, the recovery parachute is forcibly opened. The escape sequence is shown in Figure 4.1-1.

The advantage of this concept are:

- o Low complexity
- o Low weight
- o Smaller opening required for ejection

The disadvantages of this concept are:

- o Good for low speed escape only - qualified up to 315 KEAS
- o Significant vehicle roll, yaw or pitch rates at escape may cause problems

The extraction system is limited to low speed escape conditions during launch, approach and landing phases of both HVT vehicles. It is not feasible to expand this escape capability to hypersonic conditions. Therefore, it is not considered to be a viable option for hypervelocity vehicles.

4.2 CONCEPT 2 - OPEN EJECTION SEAT

Various types of high performance ejection seats, such as ACES II and CREST demonstration seat, have been or are being developed for military aircraft. Of these, CREST has higher altitude (70,000 feet) and higher speed (700 KEAS) capabilities. The CREST escape envelope is shown in Figure 4.2-1.

A CREST ejection seat system will include: A catapult; a wind protection system; integrated harness; rocket propulsion system with a thrust vector control and/or reaction control jets; flight control system for flight stabilization and acceleration control; fins and/or drogue parachute for flight stabilization; personnel recovery parachute; life support system; survival kits; and emergency harness release mechanism.

At ejection initiation, the canopy is jettisoned and the catapult system ejects the seat and guides it from the cockpit. The propulsion system is activated at the end of the

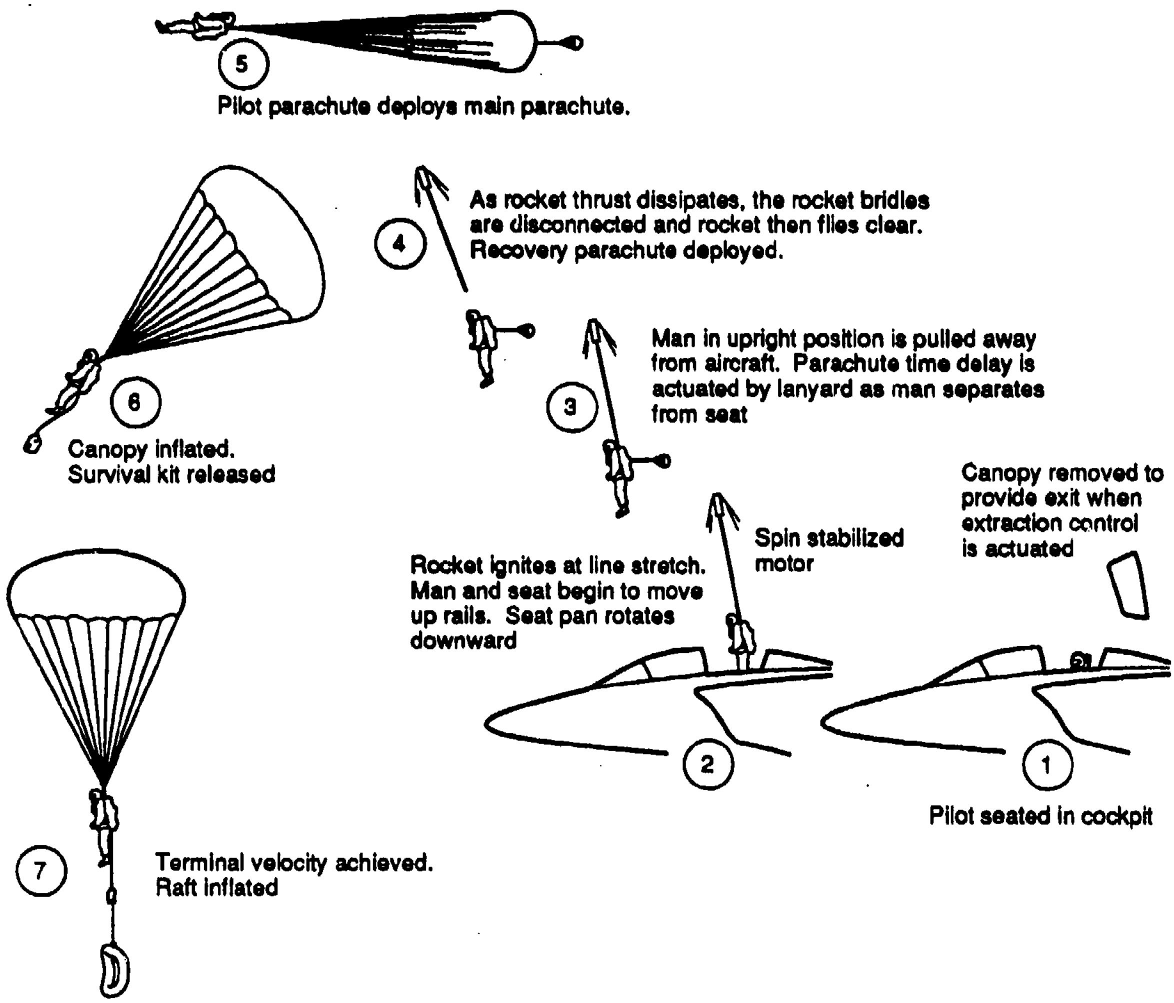


Figure 4.1-1. Extraction System Ejection and Recovery Sequence

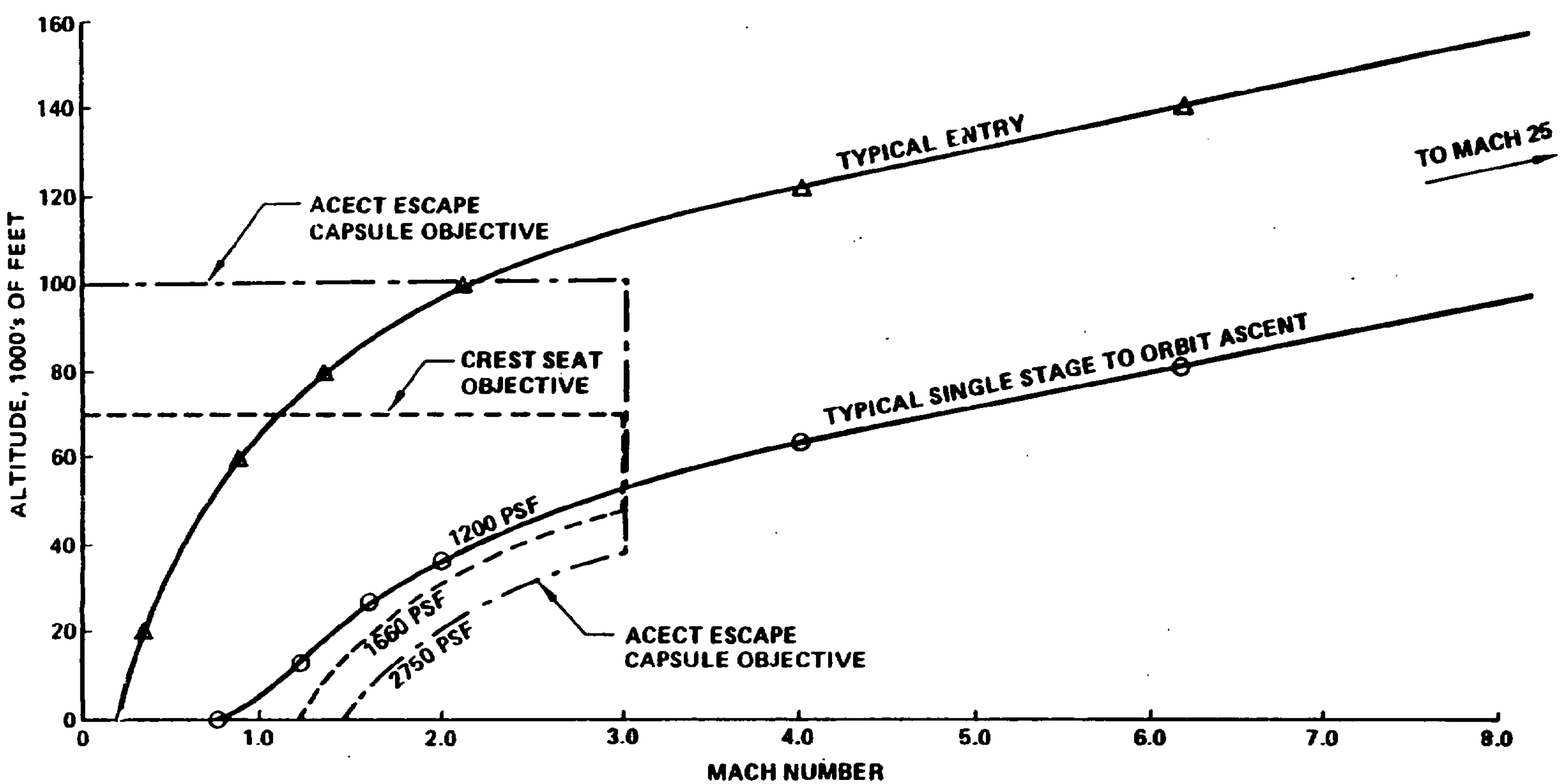


Figure 4.2-1. Ejection Seat and Capsule Performance Envelopes with Typical-Single-Stage-to-Orbit Ascent and Entry Profiles Shown to Mach 8

catapult phase and controls the attitude, trajectory and acceleration of the seat. Fins may be deployed during this propulsive phase for aerodynamic stability. Drogue parachute is deployed at the end of propulsive phase for deceleration and seat stabilization. The recovery parachute is deployed and the drogue is released when the seat reaches a certain speed. The opening recovery parachute force separates the crew member from the seat and lowers him with the survival kit to earth. An ejection seat escape sequence is shown in Figure 4.2-2.

The advantages of an ejection seat system are:

- Rapid escape
- Low to moderate complexity
- Zero-speed, zero-altitude capability
- Subsonic and supersonic (up to 700 KEAS/Mach 3) escape capabilities

The basic disadvantage is that it does not provide escape capability over the whole altitude-speed range. The dynamic pressure of the horizontal takeoff HVT vehicle is 2000 psf during ascent, while the maximum allowable dynamic pressure for the CREST seat is 1660 psf.

Even though new technologies have been incorporated into ejection seats, they do not alter the fact that the crew is essentially unprotected from the environment existing at the time of ejection. During hypersonic flight of the HVT vehicle, the crew will be exposed to excessively high stagnation temperature, deceleration and limb flailing due to windblast. Ejection seats are only applicable to escape during launch, shortly after launch, terminal approach and landing phases of the HVT vehicles. Pressure suits with thermal protection from aerodynamic heating can be used to extend the escape capability to about Mach 4 but not much higher. Therefore, an open ejection seat is not considered to be a viable escape system option for hypervelocity vehicles.

4.3 CONCEPT 3 - ENCAPSULATED SEAT WITH THERMAL PROTECTION

An encapsulated seat is basically an ejection seat with doors to shield the crew member from the environment during escape and to provide emergency life support environment. The Stanley B-58 and North America B-70 encapsulated seats have been developed for high speed airplanes, and work has also been done in the past on modifying a Stanley B-58 encapsulated seat for rescue from orbital flight (Reference 4). These encapsulated seats may be modified to provide escape from HVT vehicles.

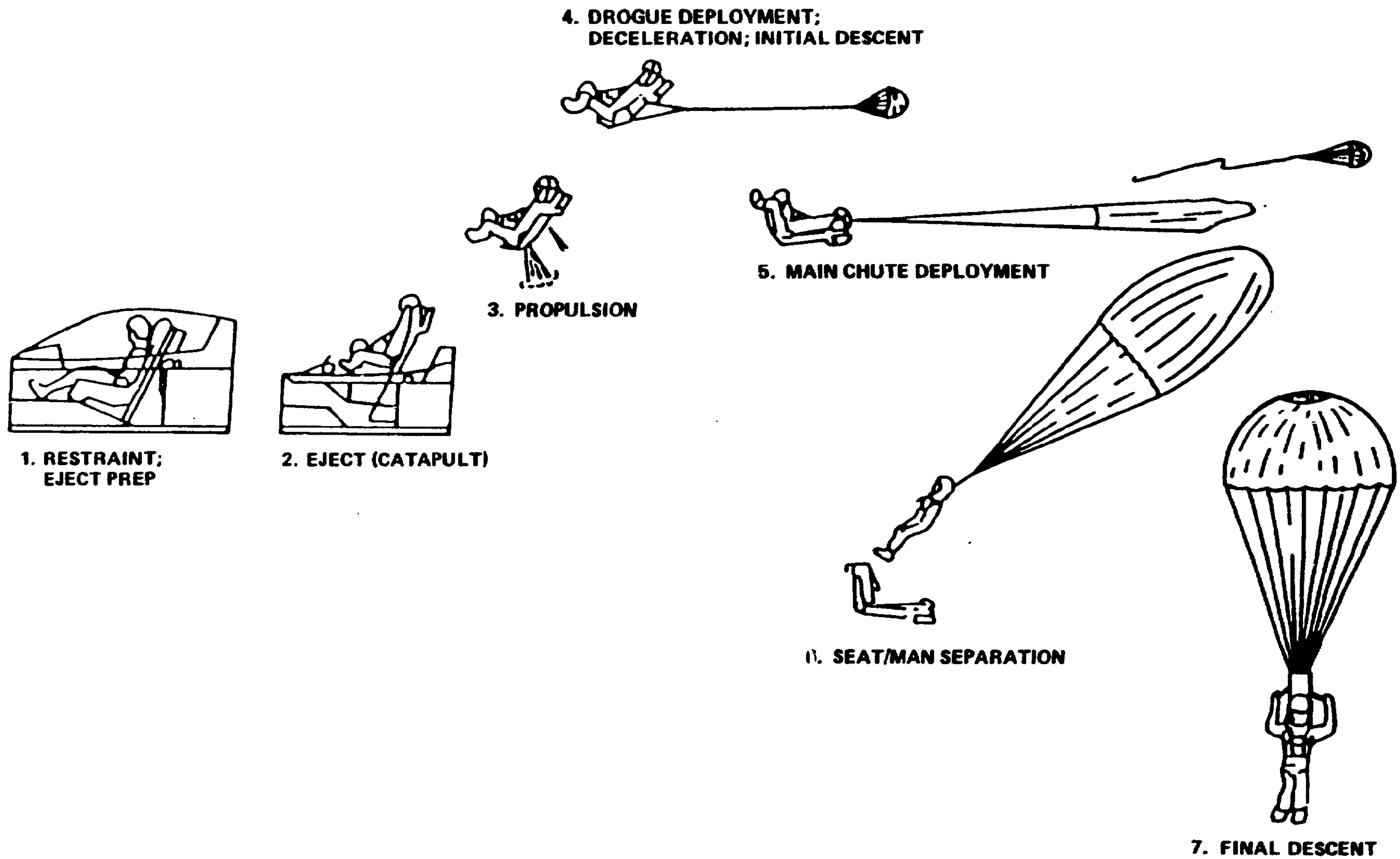


Figure 4.2-2. CREST Ejection Seat Operating Sequence

A modified B-58 encapsulated seat is depicted in Figure 4.3-1. It includes a heat shield, which can be opened, solid-propellant retrorocket engine, reaction control jets, life support system and a control system.

At the initiation of the ejection sequence due to an emergency, the doors of the encapsulated seat are closed, and the seat is catapulted. The reaction control jets are used for seat stabilization. An onboard life support system maintains the desired pressure and oxygen content in the encapsulated seat, thus eliminating the need for a pressure suit. For emergency escape during reentry or at high speeds, the encapsulated seat is oriented so the heat shield is facing forward. For orbital emergency escape, the retrorocket engines are ignited to initiate the deorbit maneuver. The encapsulated seat is then oriented so that the heat shield is facing forward, and the retrorockets are jettisoned prior to atmospheric entry.

As the encapsulated seat descends to a predetermined altitude, parachute is deployed to slow its descent and impact attenuation is provided for soft landing. At 15,000 feet, a door-seat-man separation may be used to eliminate the impact attenuation system.

The advantages of this concept are:

- o Rapid escape
- o No external rescue vehicle
- o Shirt sleeve working environment
- o Temporary shelter for cabin environmental contamination or pressure loss
- o Whole HVT flight envelope escape capability
- o Two-men encapsulated seats possible

The disadvantages of this concept are:

- o High weight
- o High volume
- o Large on-board life support system
- o Door mechanism complexity
- o Heat protection system complexity
- o Low crossrange capability

The specific requirements for this concept are:

- o Position and stabilize the capsule for thermal protection during high speed flight, reentry or deorbit

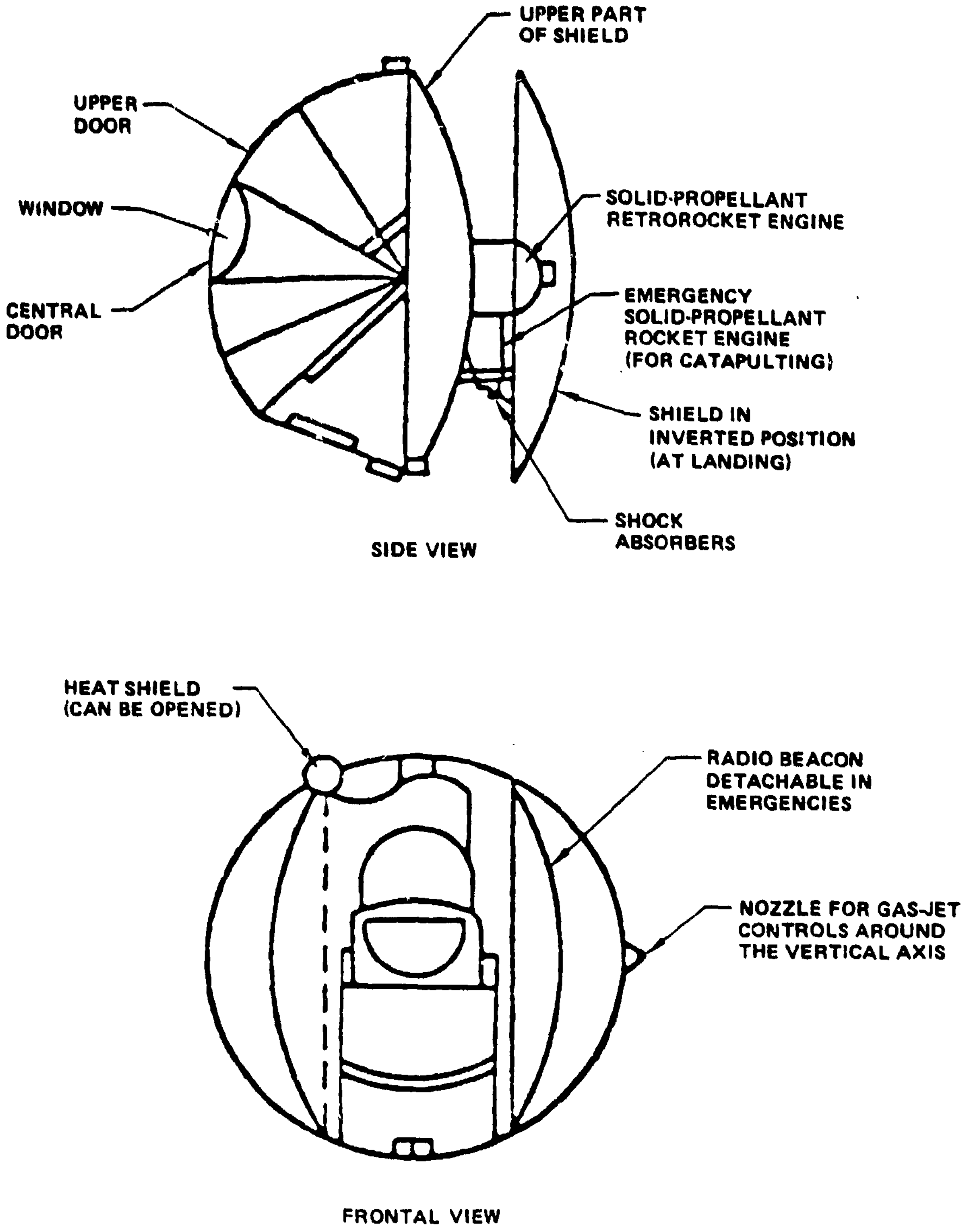


Figure 4.3-1. Encapsulated Seat with Reentry Capability

- Life support system up to 12 hours for orbital escape or 1 hour for reentry escape
- Heat shield for aerodynamic heating protection
- Deorbit capability - about 500 fps change in velocity required

The above requirements to make an encapsulated seat suitable for escape during any part of the HVV flight envelopes can be satisfied with appropriate development of design and applicable technologies. Therefore, the encapsulated seat with thermal protection is considered to be a viable option of the HVT escape system, and has been further developed. This additional encapsulated seat development is discussed in Section 5.0.

4.4 CONCEPT 4 - SEPARABLE NOSE CAPSULE WITH THERMAL PROTECTION

Separable nose capsules have been developed for fighter airplanes such as F-104 and are also being investigated under the ACECT program. Beside the escape capability during subsonic or supersonic flights of these capsules, a HVT capsule can provide the escape ability for hypersonic flight, reentry or orbital flight. The main differences will be in special provisions for protection against high structural temperatures (e.g. heat shields), retrorockets for deorbit maneuver and more extensive life support provisions. Also, part of the structural cooling system may need to be maintained.

During a flight, once the decision to escape has been made, the crew would perform a forebody separation, i.e., the nose portion of the HVT vehicle is separated from the mainbody by means of explosive bolts (or by some other means). The forebody, once it has separated, is completely sealed from the surrounding environment.

If escape occurs during orbital flight, thrust vector control positions the forebody correctly for reentry and initiates the reentry. As the descent velocity increases, the forebody is protected from reentry heating by means of a heat shield or other provisions. The same thermal protection provisions will be used for escape during reentry or high speed flight.

The forebody continues its descent until at a predetermined altitude a drogue and then a recovery parachute is deployed. The type of recovery parachute that is required would depend upon whether the capsule is recoverable or hybrid. If it is hybrid with the forebody designed to perform a seat ejection, then at the right speed and altitudes, a seat ejection may be initiated using a high performance ejection seat or an extraction system. If the forebody is designed for a ground landing, then a properly-sized parachute would be deployed to slow the descent rate of the capsule. The capsule would also require an impact attenuation system for soft landing capabilities. An escape sequence

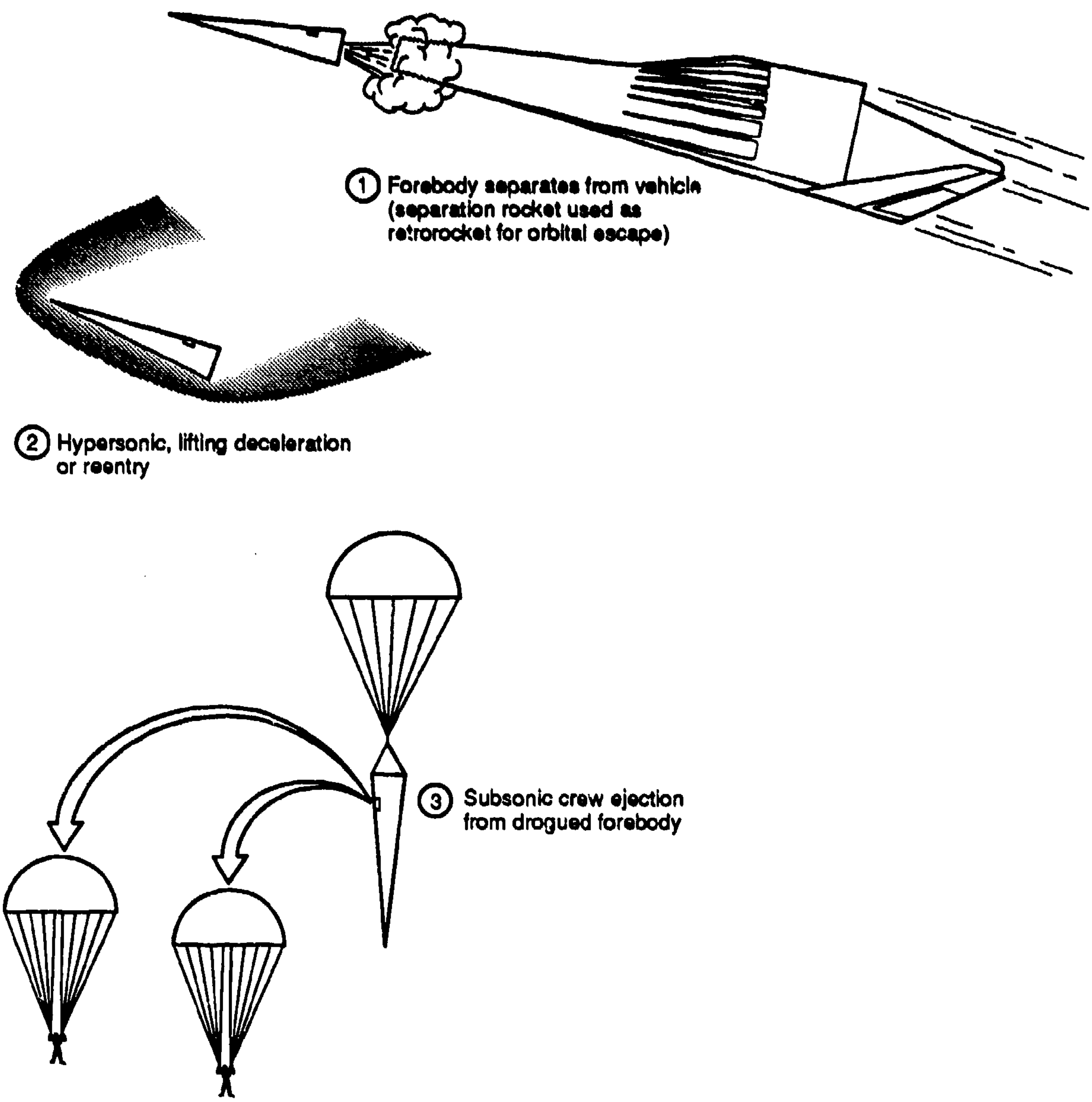


Figure 4.4-1. Separable Forebody Escape System

for a hybrid nose capsule for the horizontally launched HVT vehicle is shown in Figure 4.4-1.

The main advantage of this concept is that no external rescue vehicle is required for orbital or reentry escape, and that the forebody can be separated from the rest of the vehicle rapidly, when needed. The same escape system should also be suitable for ejection during the rest of the flight envelope. A shirt sleeve working environment can be maintained. The capsule configured with high body lift/drag ratio together with aerodynamic devices would have the high crossrange capability. A maximum of 2750 psf dynamic pressure capability of the ACECT capsule exceeds the 2000 psf requirements for the HLV (see Figure 4.2-1).

The biggest disadvantage is the expected high weight penalty, which may be unacceptable. The additional weight will come from solid bulkhead addition, heat shielding, separation mechanism, propulsion system, parachutes and impact attenuation system. Use of more advanced materials, utilizing existing heat shielding (where practical), using ejection seats or extraction systems as an alternative at low altitudes, will be considered to reduce the weight penalty as much as possible.

The other main disadvantage of this concept is that if the forebody of the HVT vehicle is damaged, then no rescue is possible.

The specific requirements for this concept are:

- o Position and stabilize the forebody for thermal protection, as required, during reentry or high speed ejection
- o Life support system up to 12 hours for orbital escape or 1 hour for reentry escape.
- o Heat protection by normal nose reentry protection system or by dedicated heat shield at aft end
- o Capsule to ground radio communication
- o High body lift to drag ratio and aerodynamic devices for crossrange capability
- o Deorbit capability

It should be feasible to satisfy the above requirements with appropriate development of design and applicable technologies. Therefore, the separable nose capsule with thermal protection is a viable option for HVT escape system.

4.5 CONCEPTS 5 - POD TYPE CAPSULE WITH THERMAL PROTECTION

This concept is similar to Concept 4, except that instead of separating the whole forebody, only part of the crew cabin is separated and used as an escape capsule. The

separation mechanism is relatively more complex, but some weight savings may be possible.

This capsule configuration also needs special provisions for protection against high structural temperatures (e.g., heat shields), retrorockets for deorbit maneuver and life support provisions for the crew. The overall crew action and the capsule events are similar to that for Concept 4, as discussed in Section 4.4. A pod type capsule escape sequence for the vertically launched HVT vehicle is shown in Figure 4.5-1.

The advantages and disadvantages and requirements of the pod-type reentry capsule are similar to that for Concept 4, except that the former may have lower weight penalty. Like Concept 4, pod-type capsule with thermal protection is a viable option for HVT escape system.

4.6 CONCEPT 6 - INFLATABLE CAPSULE WITH REENTRY CAPABILITY

The inflatable balloon escape system (Reference 4) is designed for orbital and reentry emergency escapes. The capsule is a one man escape vehicle. It consists of a nylon or fiber glass inflatable shell with outer ablative coating and inner polyurethane coating; a compressed oxygen cylinder for breathing and cooling; a nitrogen cylinder to fill the shell, a retrorocket attached to the outside of the shell, reaction jets, and life jacket.

In case of an emergency, the pilot encloses himself in the uninflated shell and leaves the vehicle. At the time for deorbiting, the capsule is turned around into the position for braking and retrorocket is ignited. The onboard computer estimates the necessary impulse for deorbit and then jettisons the retrorocket engine. After the retrorocket engine separation, the shell is filled with nitrogen and it assumes the shape of a ball. The shell is designed so that the ablative coating falls forward during reentry. At an altitude of about 15,000 feet, the external pressure gradually crumples the shell, the crewmember discards the shell and makes the descent to the ground in a parachute.

A variation in design of this inflatable capsule would allow more rapid escape. This variation allows capsule deployment and use from within the vehicle and removes the need to don a pressure suit and exit the vehicle before deployment (Figure 4.6-1). This feature allows a much more rapid escape and eliminates the encumbrance of the suit.

The advantages of this concept are:

- Rapid escape
- Low weight
- Low volume

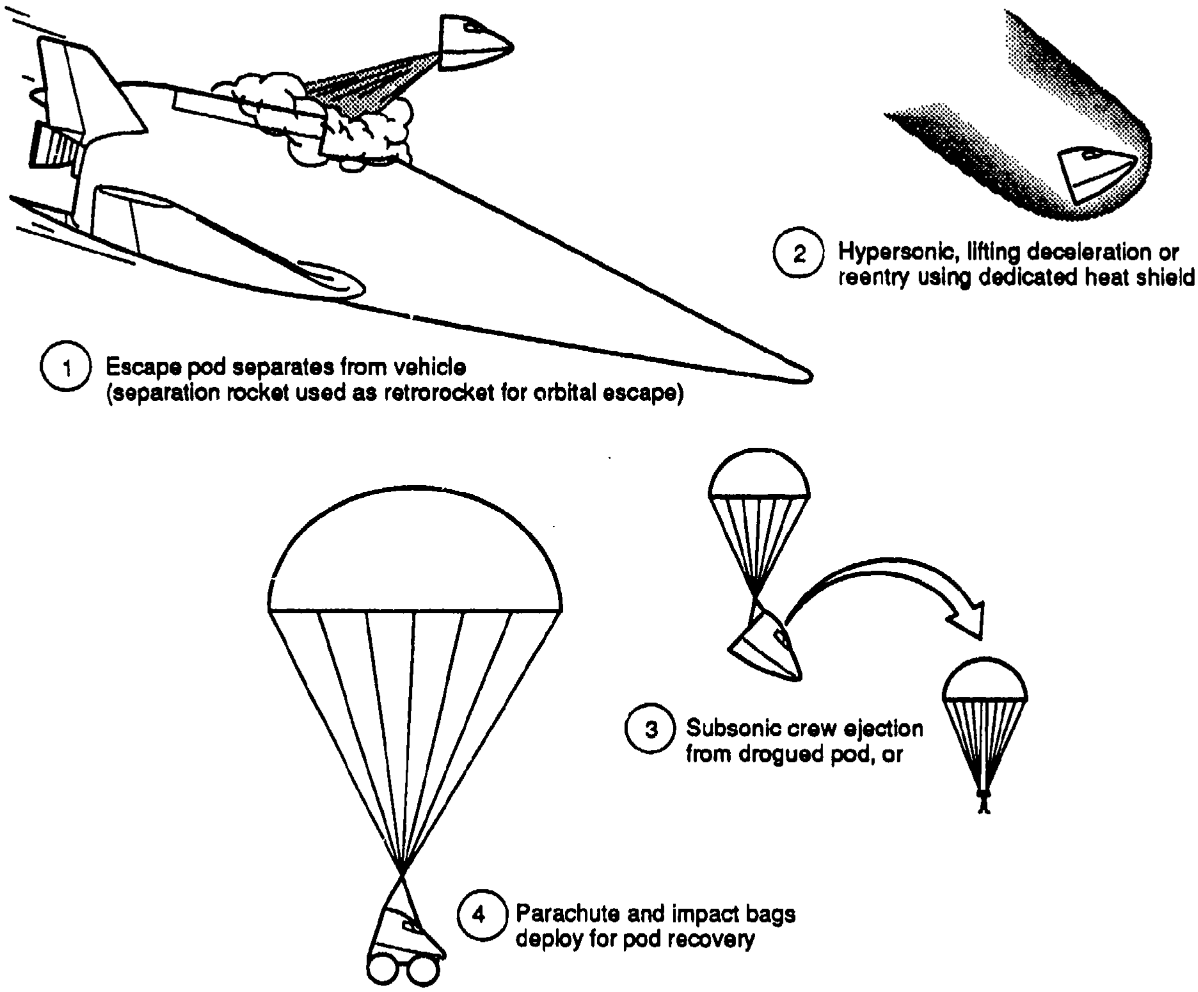
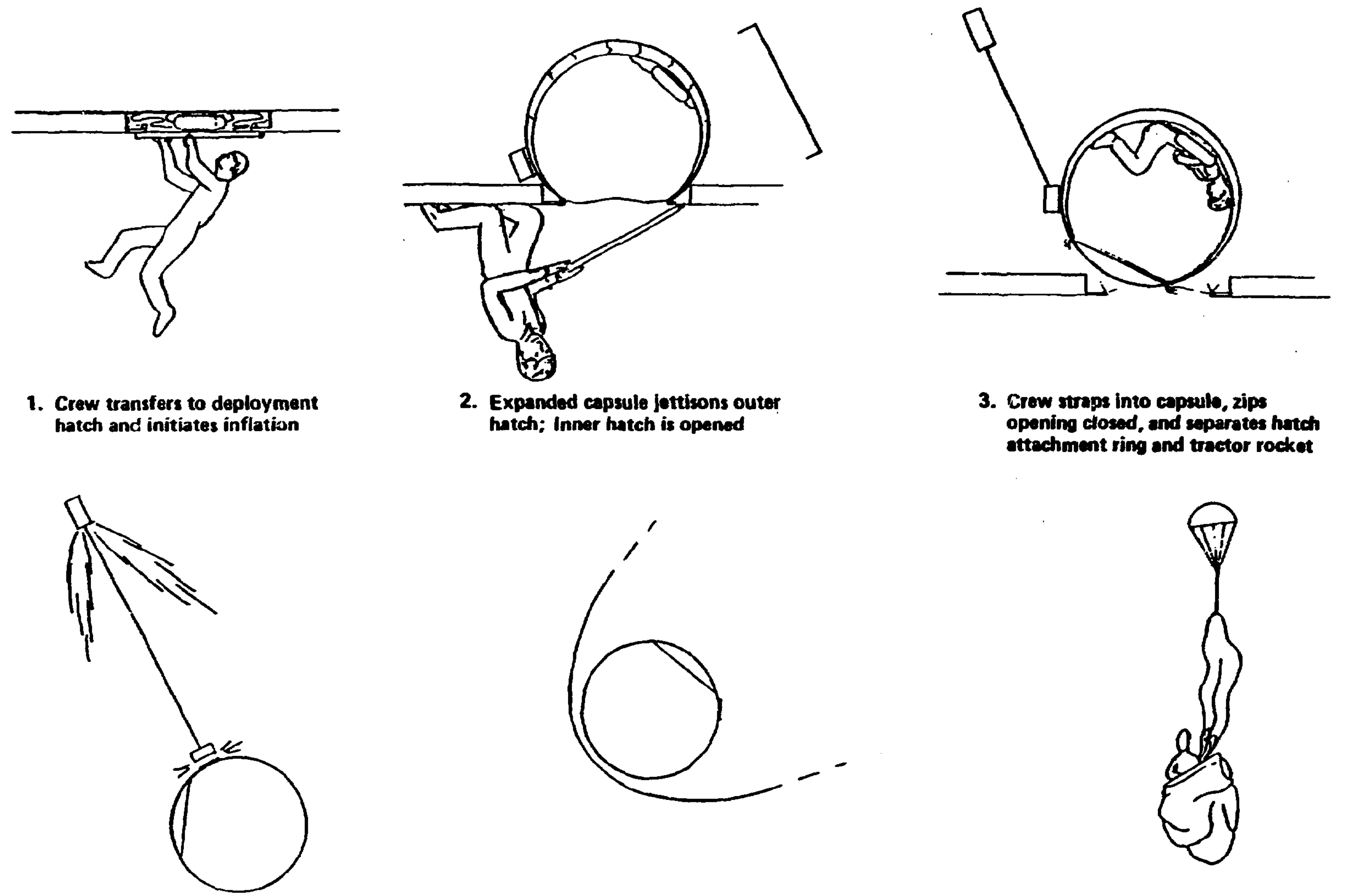


Figure 4.5-1. Pod-Type Escape System



1. Crew transfers to deployment hatch and initiates inflation

2. Expanded capsule jettisons outer hatch; Inner hatch is opened

3. Crew straps into capsule, zips opening closed, and separates hatch attachment ring and tractor rocket

4. Tractor rocket performs separation or deorbit manuver and is jettisoned

5. Capsule performs reentry

6. Crew deploys parachute from deflated capsule

Figure 4.6-1. Inflatable Capsule Escape Sequence

- No other rescue vehicle required

The disadvantages of this concept are:

- Orbital and reentry escape only. No capability for escape during atmospheric flight
- If HVT vehicle loses control causing tumbling, the crew may not be able to put on the shell
- No crossrange capability

The specific requirements for this concept are:

- Life support up to 12 hours for orbital escape or 1 hour for reentry escape
- Pressure suit during normal flight for complete protection
- Deorbit capability — 500 fps change in velocity
- Radiation protection during escape over the poles
- Capsule to ground radio communication
- Positioning and stabilization of ablative coating in forward position

Since this concept does not provide capability of escape during atmospheric flight, it was not considered further by itself. It was considered together with an ejection seat as Concept 15 in Section 4.15.

4.7 CONCEPT 7 - PARACONE WITH REENTRY CAPABILITY

The Paracone emergency escape system (Reference 5) is a gas inflatable structure shaped like a cone with a spherical nose. The crew is positioned within the cone for thermal protection. Beside the expandable structure, the paracone includes a terminal velocity impact decelerator, impact attenuation system, flotation and anti-immersion devices. These are integrated into the crew ejection seat that may have a retro unit for deorbit capability. A Paracone emergency escape system is shown in Figure 4.7-1.

In case of an emergency during orbital flight, the crew member dons a pressure suit, the seat is ejected from the vehicle, the seat is stabilized with attitude reaction jets, retrorockets are fired at the correct moment for deorbit, the retrorockets are jettisoned after rocket burnout and the Paracone inflation system is actuated to shape the Paracone around the crew. The Paracone is made of high strength steel wire screen and coated with high temperature silicones. It protects the crew member against high reentry temperatures as well as provides ground impact attenuation and flotation.

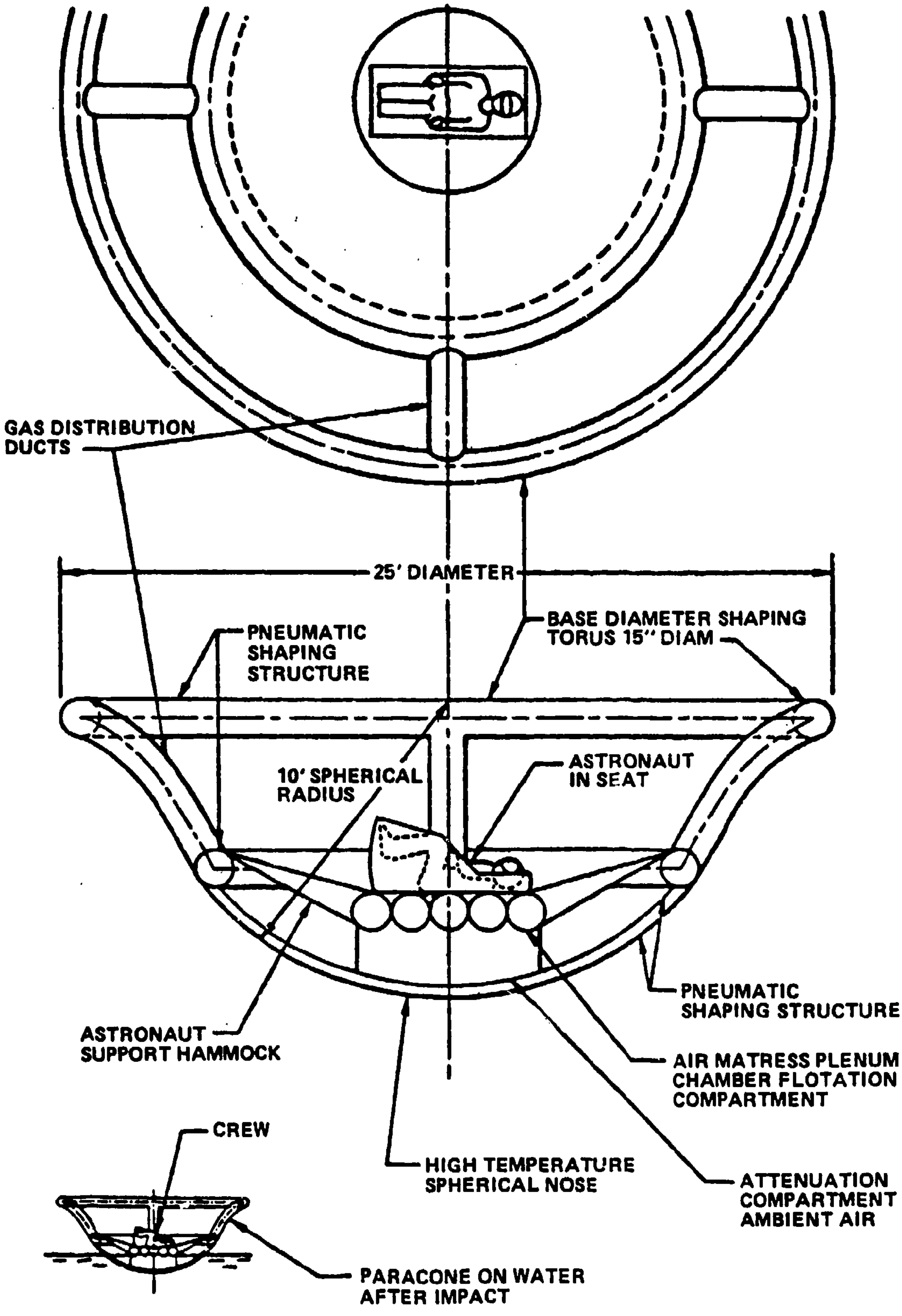


Figure 4.7-1. Paracone Emergency Escape System

If escape occurs during atmospheric flight, the crew in a pressure suit is ejected with the seat from the vehicle, the inflating Paracone spherical nose can be positioned into forward direction by attitude reaction jets for aerodynamic heating protection, if required. However, protection against high aerodynamic heating rates prior to full Paracone inflation and proper positioning is a major concern.

The advantages of this concept are:

- o Rapid escape
- o Large target for recovery
- o Low weight
- o Low volume

The disadvantage of this concept are:

- o Seat/paracone structural complexity
- o Paracone structure may require high inflation pressure.
- o Low crossrange capability
- o May not be practical for high dynamic pressure or high Mach no. conditions in the atmosphere

The specific requirements for this concept are:

- o Positioning and stabilization for deorbit, reentry and hypersonic flight thermal protection
- o Pressure suit during flight for complete protection
- o 12 hours of life support during orbital escape or 1 hour for reentry escape
- o Deorbit capability - 500 fps change in velocity
- o Radiation protection during escape over the polar orbit
- o Paracone to ground radio communication

The Paracone emergency escape system has many attractive features for escape during orbital flight. However, it is not considered to be practical for hypersonic flight, because the crewmembers will be exposed to high aerodynamic heating rates prior to full Paracone inflation and rotation of spherical nose in the forward-facing position. This concept was not pursued further.

4.8 CONCEPT 8 - MATING WITH ORBITING SPACE RESCUE STATION

In this concept, the disabled HVT vehicle mates with a space station that has previously been placed in orbit (Figure 4.8-1). This space rescue station (SRS) would provide a protective environment until a rescue vehicle arrives. The rescue vehicle would also mate with the SRS. The crew from the HVT vehicle would then transfer from the SRS to the rescue vehicle. The rescue vehicle separates from the SRS and returns to earth.

The SRS is permanently stored probably in a 300 nm circular orbit. A higher orbit would place it in the Van Allen radiation belt (although the 300 nm orbit would still fly through dangerous areas over the poles), and a lower orbit would decay too quickly. The 300 nm orbit would still have to be raised about once a year to prevent its decay.

The advantages of this concept are:

- SRS provides emergency oxygen and environmental protection until a rescue mission can be flown
- HVT vehicle is not forced to make a reentry if aerodynamic control systems or thermal protection systems failed.

The disadvantages of this concept are:

- SRS orbital decay
- Large impulse required for mating
- Precision required for mating
- Inability to provide escape for many emergency conditions
- Orbital flight rescue only
- Expensive SRS logistics
- Large on-board life support backup system

The specific requirements of this concept include:

- Oxygen for a few hours for two men while in the SRS, plus oxygen for another hour for four men
- Temperature control (provided for the HVT vehicle crew either by space suits or by the SRS)
- Barometric pressure control (provided by either the space suits or by the SRS)
- Precise mating for the HVT vehicle and the rescue vehicle to the SRS
- Rescue vehicle is required to hold four crew members
- The SRS is required to hold two crew members

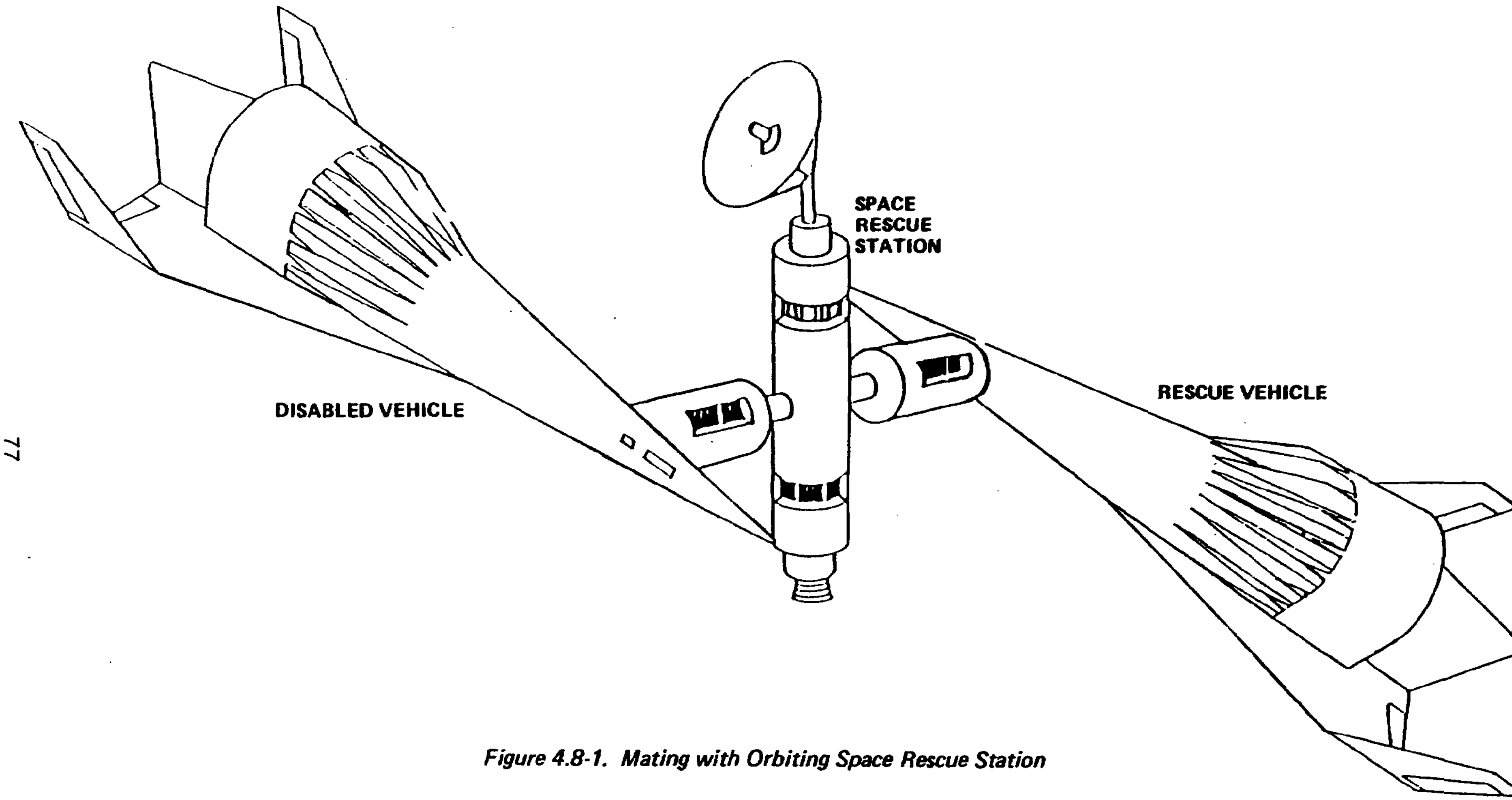


Figure 4.8-1. Mating with Orbiting Space Rescue Station

- Radio communications between SRS, HVT vehicle and ground stations
- HVT vehicles need the ability to make in-plane and out-plane orbital maneuver

One difficulty with this approach is providing a station that is reachable from the vehicle. Unless the vehicle is placed in an orbit very close to the SRS, some degree of maneuvering capability will be required, provided by the vehicle's propulsion syste (if it's still operative). If they are in different orbital planes, a very energetic maneuver is required. A ten degree plane change requires about 4360 fps velocity change, which would require a hydrogen-oxygen propellant mass equal to 35 percent of the delivered mass. For a 100,000 pounds orbiter, this amounts to 35,000 pounds of fuel, which is 4 times the present payload of 15,000 pounds without crew escape. An atmospheric plane change maneuver would require less propellant, but if the vehicle still had this capability, it would also be capable of re-entry.

Once the vehicle and the SRS are in the same plane, they must orbit at different average altitudes so that their differing orbital speeds will allow them to move toward each other. If the SRS is in 300 nm orbit and the HVT vehicle is in a 100 nm circular orbit, a rendezvous opportunity would ope only every 54 hours. Orbits closer together require longer waits. At this time two maneuvers are required: one to raise the orbit's apogee to 300 nm and then, when the apogee is reached about 45 minutes later, to circularize the orbit. These maneuvers require a 683 fps velocity change or about five percent of the delivered mass with hydrogen/oxygen propellants.

The logistics involved with a SRS system could be very expensive. If total coverage for all posigrade orbits is desired and the stranded crew has the ten degree plane change capability described earlier, the SRS orbital planes must be spaced 20 degrees apart and the system will require 41 stations. If the 54 hour maximum wait for a rendezvous opportunity is to be reduced, more than one station is required for each orbital plane. For example, 82 stations reduce the wait to 26 hours or less, and 164 reduces it to under 13 hours. This number can be reduced by limiting the orbital planes the HVT vehicle missions are flown in. This, however, eliminates the flexibility that is one of the primary advantages of having HVT vehicles.

Since maximum of 55 hours is required for orbital maneuvers, the on-board backup life support system requirement is large compared to other orbital escape concepts that do not use SRS.

For all its expense, an SRS system provides very little capability. This concept is unusable for any emergency except failure of the thermal protection and aerodynamic

control systems. Propulsion, navigation and reaction control system failures put the SRS out of reach. Also, no emergency escape capability is provided for escape during atmospheric flight or reentry. This concept is, therefore, not considered to be a viable option for the whole flight regime.

4.9 CONCEPT 9 - ROCKET-PACK ESCAPE TO SPACE RESCUE STATION

In this concept, the crew leaves the disabled HVT vehicle by using a rocket-pack to reach a SRS. (Figure 4.9-1).

In case of an emergency requiring exit from a HVT vehicle, the crew make an escape by simply donning the rocket pack and leaving the HVT vehicle. If the HVT vehicle is pressurized then the cabin must be depressurized before any escape hatches can be opened. Once the rocket packs are donned and the escape hatch is opened, then the crew can maneuver to a space rescue station (SRS). The SRS would provide environmental protection until a rescue vehicle arrived. At this time the crew would transfer from the SRS to the rescue vehicle. The vehicle then returns to earth.

The advantages of this concept are:

- o Rapid crew removal from the HVT vehicle if necessary
- o SRS provides emergency oxygen and environmental protection until a rescue is flown.

The disadvantages of this concept are:

- o Storage and maintenance of the rocket packs
- o The time required to don space suits and rocket packs
- o Escape and entrance hatches must be larger to accommodate the rocket packs and the astronauts
- o SRS orbital decay
- o Expensive SRS logistics
- o Large life support system
- o Large propulsion system
- o Radiation protection required during escape over the polar areas
- o Good for orbital flight rescue only

The specific requirements for this concept include:

- o An easily accessible storage place for the rocket packs
- o Space suit must provide up to 55 hours or so of oxygen for each man, exact number depending upon the number of SRS

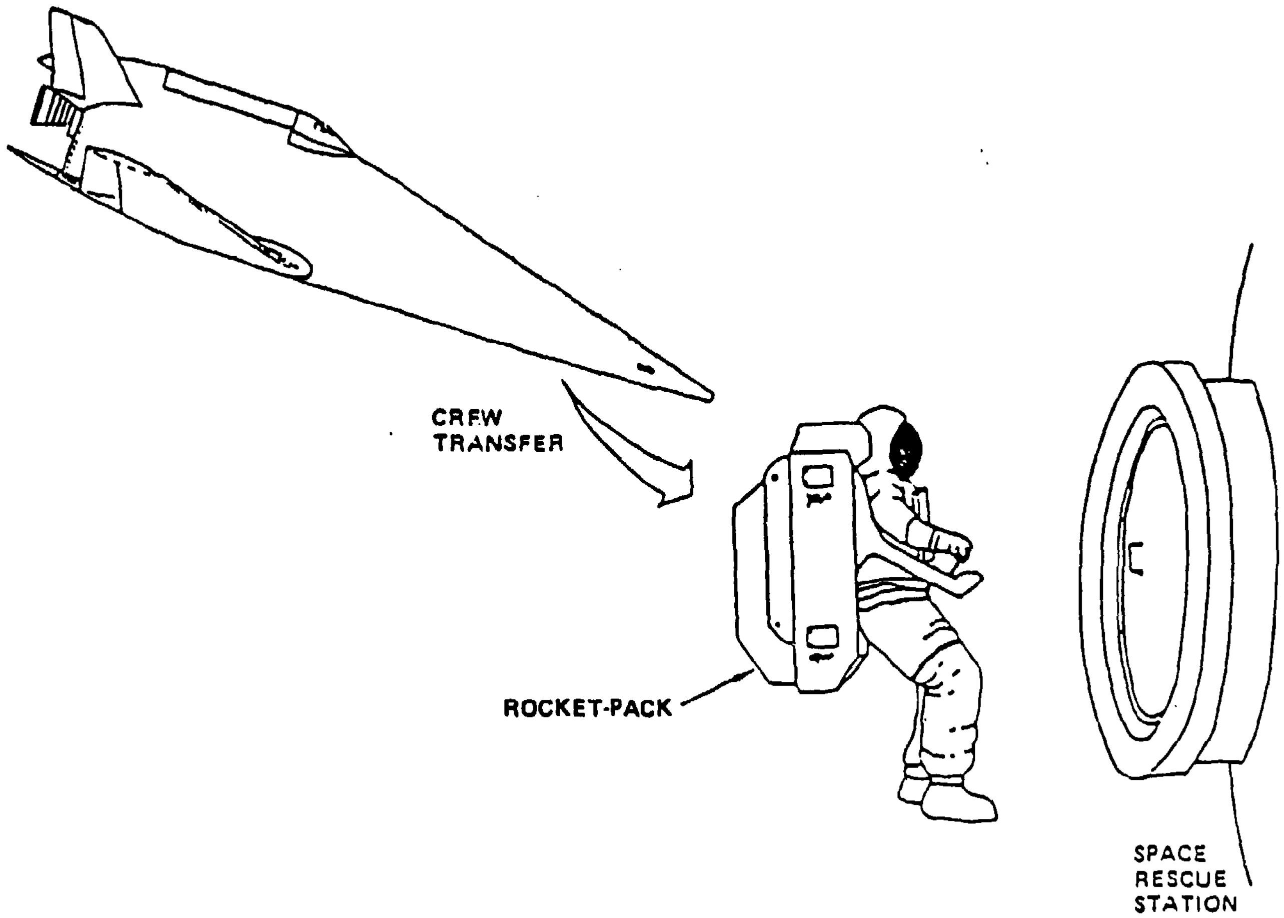


Figure 4.9-1. Rocket-Pack Escape to a Space-Rescue Station

- The rocket packs must provide enough maneuverability for the astronauts to enter exit hatches and orbital maneuvers
- Communication must be provided between the astronauts and the rescue vehicle
- Radiation protection may be required for polar flights

Like Concept 8, this concept also requires a large propulsion system (although much smaller than in Concept 8) from the rocket-pack and a large life support system for orbital maneuvers. The velocity requirements for orbital maneuvers and the emergency life support requirements are the same as Concept 8. The SRS logistic is very expensive.

This concept provides no emergency escape capability during atmospheric flight or during reentry. Therefore, it is not a viable option for the whole flight regime.

4.10 CONCEPT 10 - ROCKET-PACK ESCAPE TO A REENTRY RESCUE CAPSULE

This concept is similar to Concept 9 discussed in Section 4.9, except that the space rescue station is replaced by a capsule, which has the capability to deorbit to reenter the atmosphere and land (Figure 4.10-1).

As in Concept 9, in case of an emergency requiring exit from the disabled HVT vehicle, the crew members would don the rocket packs and maneuver to the rescue capsule. The crew would then begin procedures to deorbit the rescue capsule and use it to reenter the atmosphere and land, as indicated in Figure 4.10-2. The landing point is selected by timing the deorbit maneuver.

The advantages of this concept are:

- Rapid separation of the crew from the HVT vehicle
- Once the crew has entered the rescue capsule, reentry can begin immediately since there is no waiting for the rescue vehicle
- The rescue capsule is already in orbit and is always in a state of readiness; this prevents any delays in launching a rescue vehicle
- No other personnel are required in space to complete the rescue
- A heavy capsule does not have to be carried on the HVT vehicle all the time

The disadvantages to this concept are:

- Rescue capsule orbital decay
- Orbital flight rescue only
- Expensive rescue capsule logistics
- Large life support system during orbital maneuver

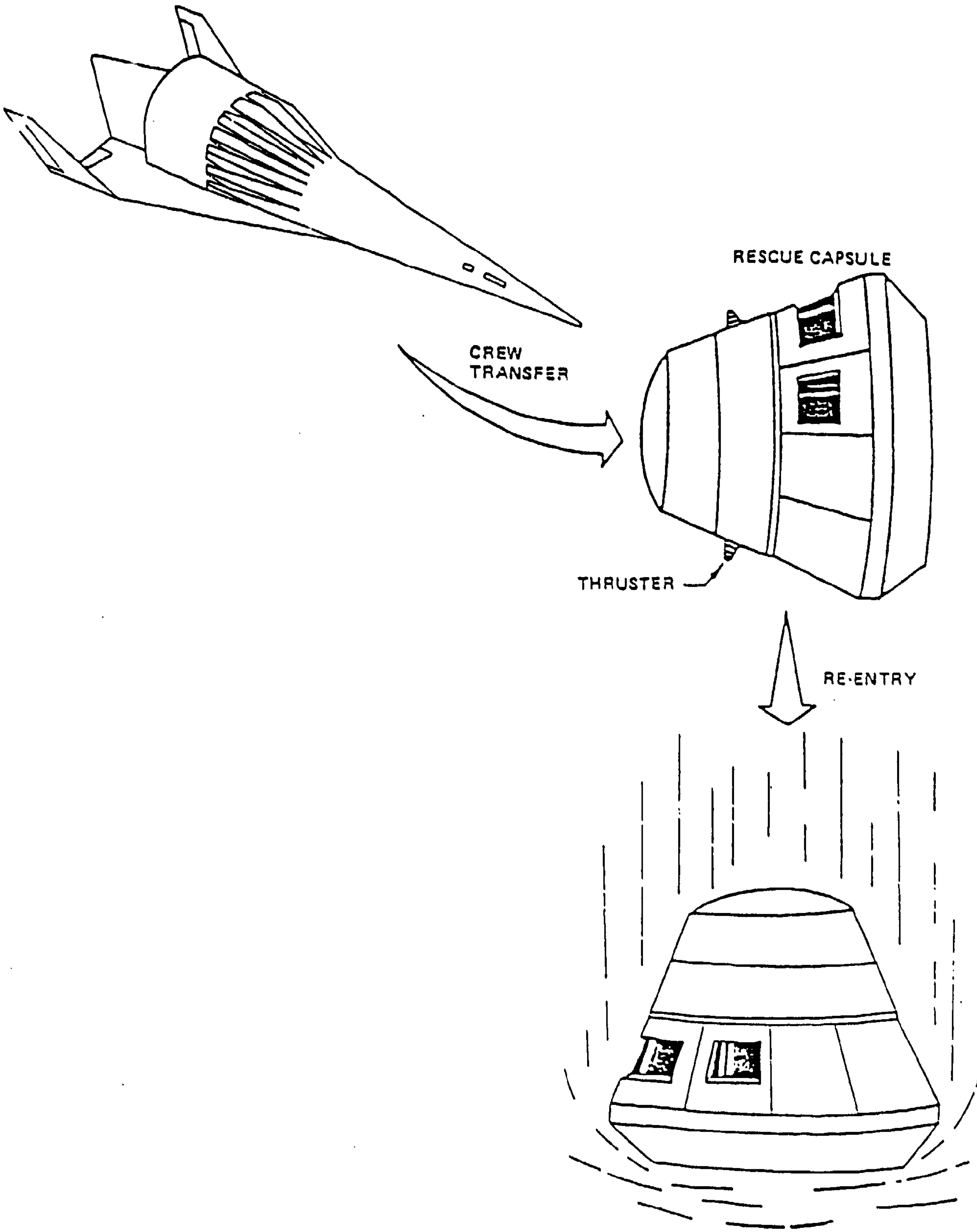


Figure 4.10-1. Rocket-Pack Escape to a Reentry Capsule

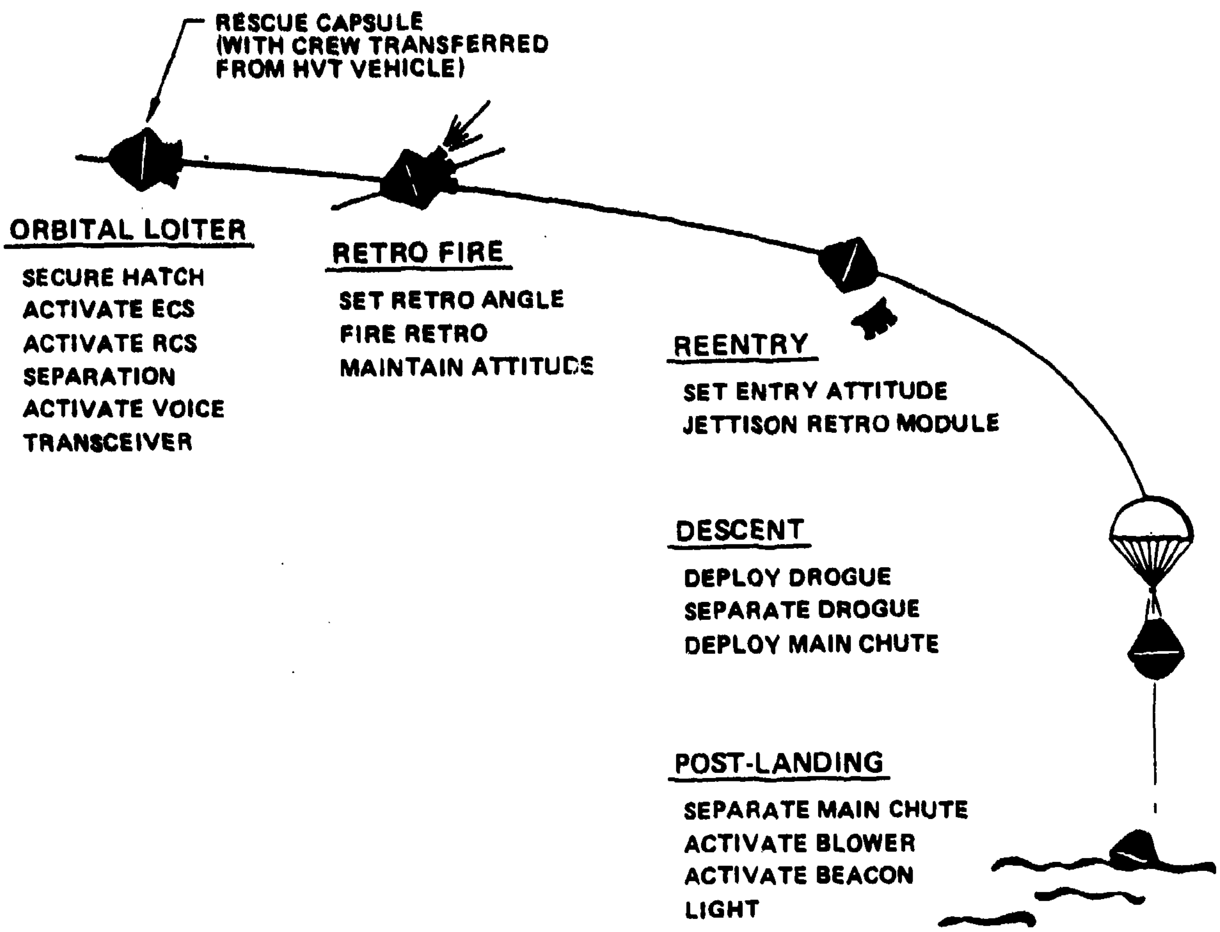


Figure 4.10-2. Sequence of Events During Rescue Capsule Reentry

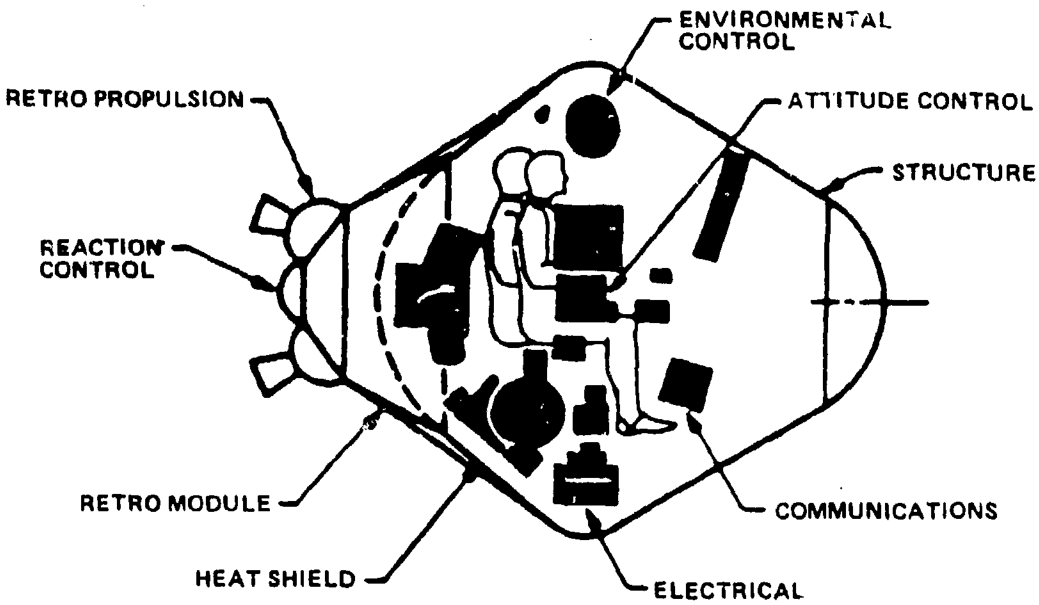


Figure 4.10-3. A Candidate Rescue Capsule Configuration

4.11 CONCEPT 11 - MATING WITH RESCUE VEHICLE

In this concept, if an emergency rescue is required, a rescue vehicle, which may be another HVT vehicle, is launched to rendezvous with the disabled HVT vehicle by using an atmospheric plane change maneuver. The disabled HVT vehicle's crewmembers then transfer to the rescue vehicle either by docking (See Figure 4.11-1) or by extra vehicular activity (EVA). The vehicles separate and the crew return to earth. The vertically-launched HVT vehicle could use a specially designed rescue pallet as shown in Figure 4.11-2 for docking, EVA and crew storage purpose.

The advantages of this concept are:

- o Concept does not deprive the HVT vehicle of payload
- o Does not require the cost or complexity of the SRS or any other satellite
- o Another HVT vehicle may be used as the rescue vehicle
- o No emergency orbital maneuver capability required

The disadvantages of this concept are:

- o Rapid escape impossible
- o Crewmembers stay with disabled HVT vehicle for a long time
- o For some missions, disabled HVT vehicle's orbit may decay before rescue is possible
- o Control system failure may make rescue impossible due to high rotation rates
- o No escape capability for atmospheric flight or during reentry

The specific requirements for this concept include:

a. Accommodation for up to four men aboard the rescue vehicle
b. Emergency oxygen for up to 12 hours required for rescue
c. Maintenance of barometric pressure of about 8 psi in the disabled vehicle cockpit or pressure suits
d. Temperature control within the comfort zone
e. Precise mating capabilities of the rescue vehicle
f. Communications between the HVT vehicles and the ground
g. No tumbling for docking or low rotation rate for EVA
h. Pressure suits are required for complete protection during EVA

The major concern with this concept is that it requires the crew to stay with the disabled HVT vehicle for a long time. Some emergencies require an exit from the HVT vehicle within a few seconds. A rescue by another HVT (or similar) vehicle may require

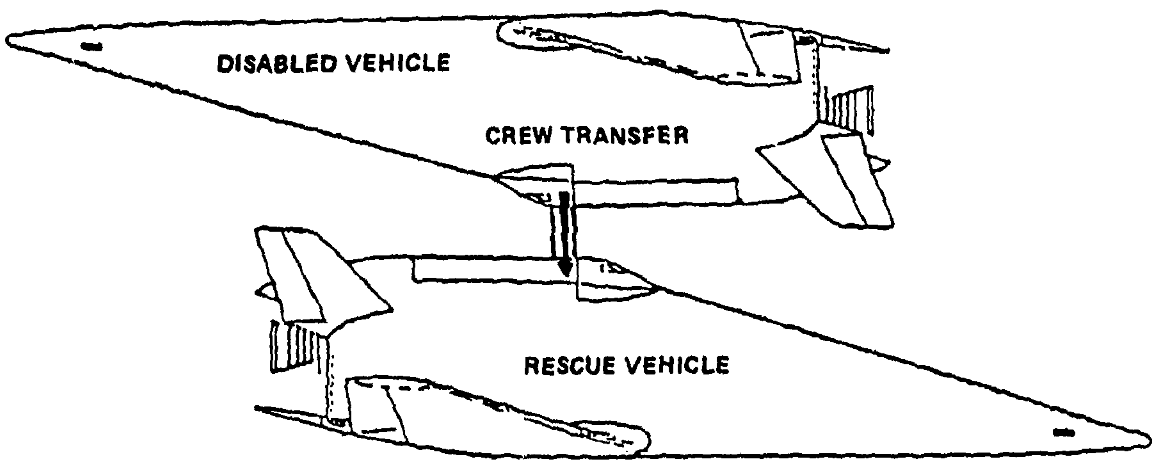


Figure 4.11-1. Mating with Another HVT Vehicle

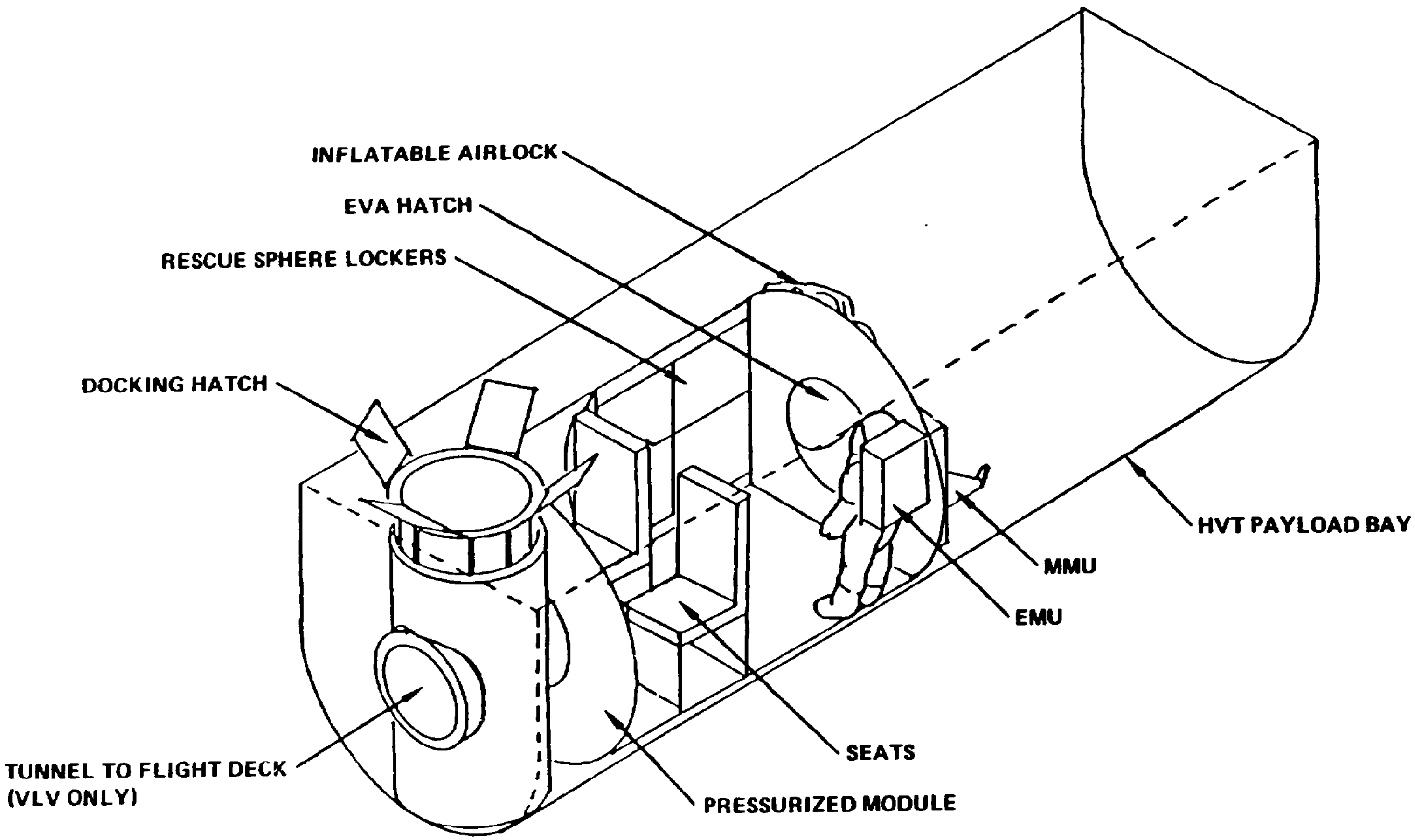


Figure 4.11-2. Rescue Pallet Showing Possible Equipment

up to a few hours, depending upon how the rendezvous is implemented. Normally, for the polar orbital missions, the orbital plane will pass through the launch plane once every 12 hours. Thus, the rescue vehicle will probably have to be launched parallel to the equator, turned in flight at the precise moment to align itself with the disabled vehicle's orbital plane and then made to enter an elliptical orbit to catch the disabled vehicle. For some missions, when the disabled HVT vehicle is in a rapid decaying orbit, the rescue mission may be impossible.

Like Concepts 8 to 10, this concept is applicable only for orbital flight phase of the HVT vehicles. No escape capability is provided for atmospheric flight or during reentry. Thus, this concept is not a viable option to provide emergency escape capability during the whole flight regime of the HVT vehicles.

4.12 CONCEPT 12 - NON-REENTRY CAPSULE ESCAPE TO RESCUE VEHICLE

This concept is similar to Concept 11 in that a rescue vehicle is launched to rescue the disabled HVT vehicle crew. However unlike in Concept 11, in this concept, the crew exits from the HVT vehicle in a non-reentry capsule immediately to wait for the rescue vehicle (Figure 4.12-1). This capsule is not designed for reentry into the earth's atmosphere and thus can be relatively lighter. It can be an erectable or inflatable capsule or an encapsulated seat, which has propulsion system for separation and emergency life support system to provide life support while the crew is waiting for rescue vehicle. The separation rocket could move the capsule to higher orbit if necessary to prevent it from rapid orbit decaying. The rescue vehicle with mechanical robot arm retrieves the capsule into the payload bay at rendezvous. A rescue pallet similar to the rescue pallet in Concept 11 with less docking equipment could be used in the vertically launch HVT vehicle's payload bay.

The advantages of this concept are:

- o Rapid escape
- o Does not require the complexity or cost of the SRS or any other satellite
- o Crew can use the non-reentry capsule as a temporary shelter in case of fire, environmental contamination or pressure loss

The disadvantages of this concept are:

- o Crew may not have time to enter inflatable capsule if catastrophic pressure loss
- o Larger escape hatches need to deploy the capsule
- o Suitable for orbital flight only

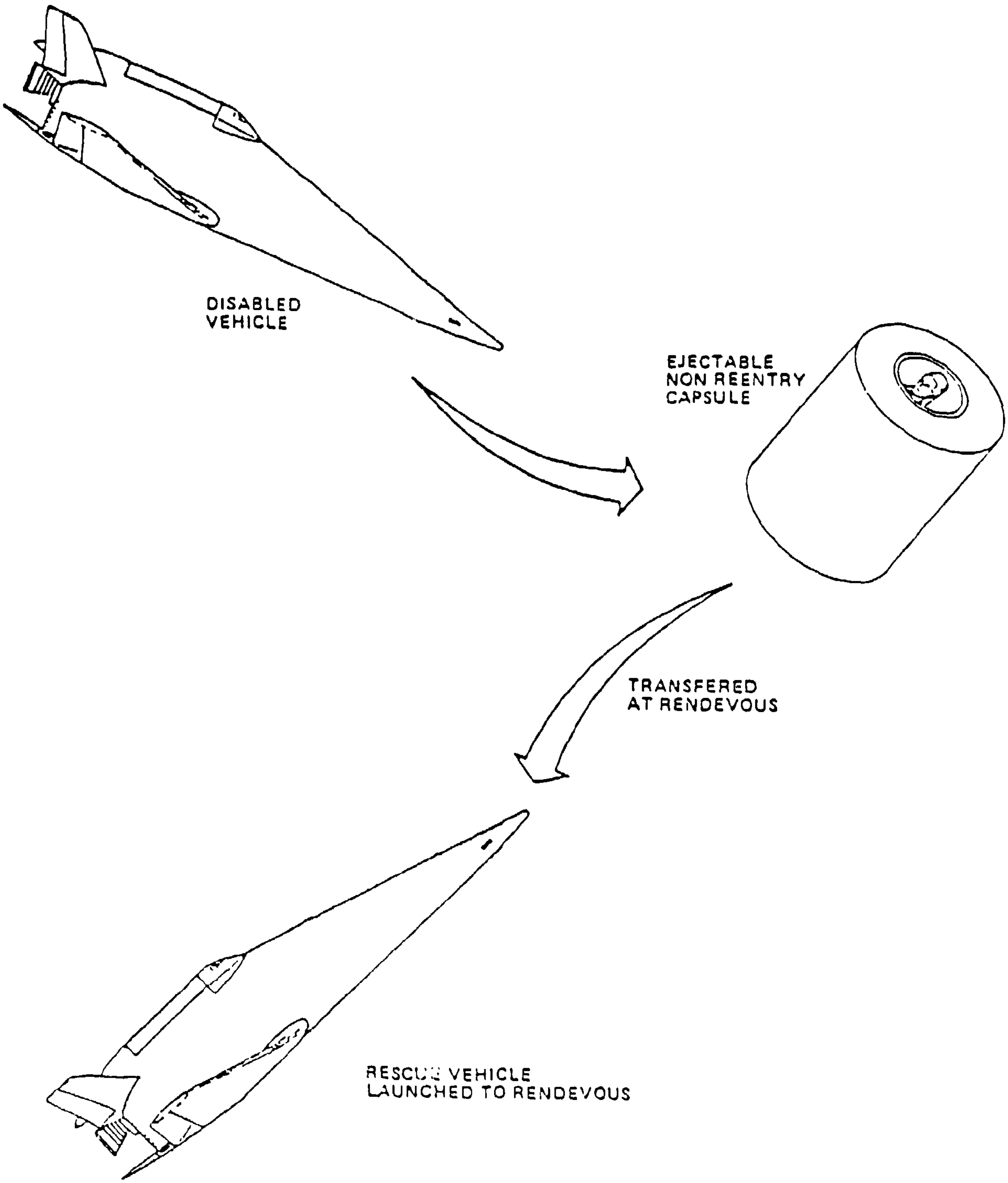


Figure 4.12-1. Non-Reentry Capsule Escape to a Rescue Vehicle

The specific requirements for this concept include:

- One or two crew capsule
- Emergency life support system up to 12 hours
- Ability to be retrieved by the rescue vehicle - requires low tumble rates for recovery by rescue crew EVA or remote manipulator
- Precise rendezvous maneuver execution
- Communication capability with the rescue vehicle and the ground

This concept also does not provide any emergency escape capability during high speed atmospheric flight or during reentry, and is thus not a viable candidate for HVT escape over the whole flight regime.

4.13 CONCEPT 13 - EJECTION SEAT WITH ORBITAL RESCUE

This escape system concept (Figure 4.13-1) consists of:

- Basic escape concept 2, an advanced, CREST derived, open ejection seat with Mach 3 capability above 50,000 feet and 700 KEAS capability below 50,000 feet.
- An advanced 8 psi pressure suit and
- Basic escape Concept 12, an orbital rescue system consisting of one or more HVT vehicles capable of carrying a rescue pallet equipped with accommodations and life support for the survivors and any equipment necessary for crew transfer, such as a robot arm, manned maneuvering unit (MMU) or docking collar.

The escape sequence during both ascent and descent at speeds below Mach 3 would be very similar to the CREST escape sequence shown in Figure 4.2-2. The seat would have a more capable propulsion system than most current seats allowing safe escape from the launching pad or runway, initial ascent and final approach from both the VLV and HLV.

Emergencies occurring during the orbital phase that result in the vehicle being rendered incapable of performing a safe reentry will require a rescue mission. While a dedicated, unmanned rescue vehicle is possible, it is probably safe to assume because of economical concerns that the rescue vehicle will be an HVT vehicle similar to the disabled craft carrying a rescue pallet in its payload bay as discussed earlier. Such a mission could be launched from the ground or from an orbiting station using an aerodynamic plane change maneuver.

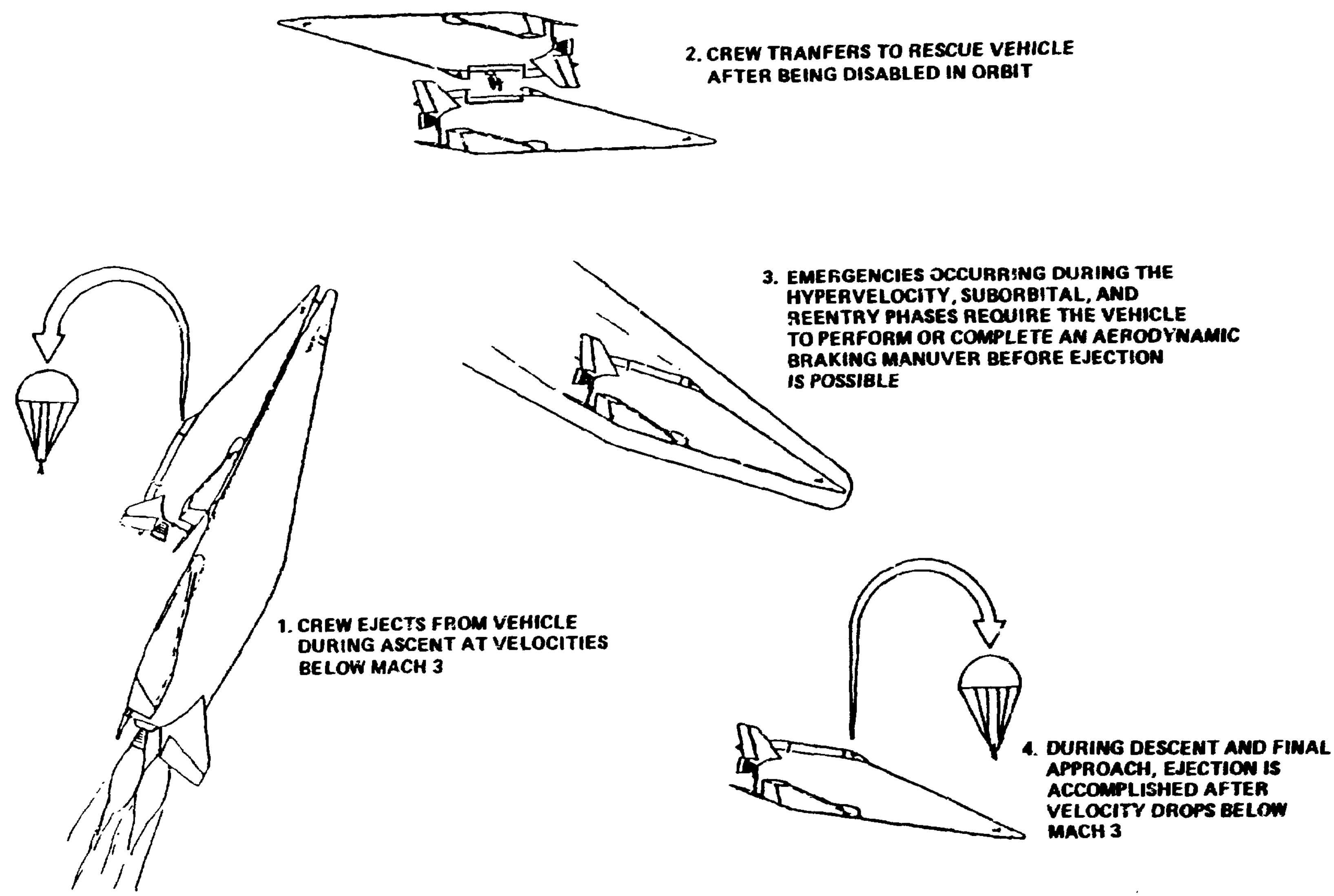


Figure 4.13-1. Ejection Seat with Orbital Rescue

Since this concept envisions the crew to be provided with pressure suits, docking the two vehicles is not necessary. The crew can transfer to the rescue vehicle by extra vehicular activity (EVA) exiting either through the ejection seat hatches, main entry hatch, or the VLV payload bay (there is no crew access to the HLV payload bay), and assisted by either a rescuing crewmember with EVA equipment or a shuttle type robot arm. The rescue vehicle then performs a normal reentry and landing.

A variation on this concept is the use of an inflatable shelter in place of a pressure suit during orbital escape. The shelter would be inflated and deployed from a special hatch eliminating the need for pressure suits during orbital flight. A grappling device on the shelter's exterior would allow retrieval from the outside of the damaged vehicle by the rescue vehicle's robot arm or EVA of the crew members. In the event of an emergency, the crewmembers leave their seats and move to the shelter hatch, inflate the shelter, enter and seal it. The process would take about 30 seconds. If the cabin is permanently uninhabitable, as from a major structural failure causing decompression, the crew remains in the shelter until rescued. An emergency such as a fire or toxic gas release, however, only requires the crew to remain in the shelter while the cabin air is automatically vented (extinguishing the fire or venting the contaminants). After repressurization, they can reenter the cabin and continue the mission. If needed, the shelter could be detached from the vehicle and recovered independently.

The advantages and disadvantages of this concept are listed on Table 4.13-1.

The specific requirements for development of this concept include:

- o A minimally encumbering 8 psi pressure suit and a 12-hour emergency life support system; or
- o An inflatable shelter deployable from a special hatch near the crew station with a 12-hour life support capability; and
- o A rescue pallet capable of being mounted in a HVT vehicle payload bay and launched on two or three hours notice.

The primary problem with this concept is that this concept provides no immediate escape capability between the time the vehicle exceeds Mach 3 and when it enters a stable orbit on ascent and after its deorbit maneuver until it slows below Mach 3 during reentry. During these flight phases, the vehicle must be able to perform a normal aerodynamic deceleration or reentry. This may not be a problem if the emergency is due to failures such as a main propulsion system shut-down during ascent or environmental control system failure. However, a more serious failure, due to an onboard explosion or

Table 4.13-1. Evaluation Of Escape Concept 13 – Ejection Seat With Orbital Rescue

Advantages	Disadvantages
Ejection seats have a minimal weight and design impact on the vehicle.	No escape capability for catastrophic failures during most of the proposed missions.
Orbital rescue involves capabilities already available or being developed for HVT vehicles for other reasons.	Pressure suit needed for emergency life support.
Low to moderate development risk for "soft" suit.	Requires a dedicated space rescue mission.
(Inflatable shelter can eliminate pressure suit requirement in orbit and have low cost and risk.)	High development risk for total counter pressure garment.
	"Soft" suit as encumbering as current pressure suits.
	(Inflatable shelters offer no pressure protection during atmospheric flight phases and require time to deploy and enter.)

hostile action, that damaged the thermal protection or aerodynamic control may make crew recovery impossible.

This concept, therefore, does not meet the SOW requirement for survivable escape and recovery throughout all flight phases allowed by the vehicle's performance envelopes, and was not developed further.

4.14 CONCEPT 14 - EXTRACTION SYSTEM WITH ORBITAL RESCUE

This escape system concept consists of:

- o Basic escape Concept 1, a tractor rocket extraction system providing escape capability up to about 315 KEAS (340 psi);
- o An advanced 8 psi pressure suit; and
- o Basic escape Concept 12, an orbital rescue system consisting of one or more HVT vehicles capable of carrying a rescue pallet equipped with accommodations and life support for survivors and any equipment necessary for crew transfer.

The orbital rescue description of this concept is the same as that given for Concept 13, including possible use of an inflatable shelter variant. In this version, however, an extraction system is used in place of ejection seats (see Figure 4.1-1).

Use of this approach would save a lot of weight and have only a small impact, if any, on the VLV escape envelope, since the aerodynamic loads this vehicle encounters never exceeds 400 psf. The HLV, however, which typically accelerates to between 800 and 2000 psf (468 to 768 KEAS) soon after launch, would spend very little time in the system's ejection envelope. Also, without the physical support of the seat structure, it may be difficult for a crewmember to endure the acceleration required to escape from a vehicle that explodes before or just after launch.

Currently available extraction systems have no life support capability and are therefore limited to use below 15,000 feet, but a small oxygen tank and regulator could be included with the current parachute container (in the seat back or pan on past systems) with only a slight increase in weight and volume.

The advantages and disadvantages of this concept are noted in Table 4.14-1.

This concept requires development of:

- o An extraction rocket system with enhanced propulsion capability and life support system;
- o A minimally encumbering 8 psi pressure suit with a 12-hour emergency life support system; or

Table 4.14-1. Evaluation Of Escape Concept 14 – Extraction System With Orbital Rescue

Advantages	Disadvantages
Extraction rockets have less development risk, cost, weight and design impact than advanced ejection seats.	Extraction rockets further reduce mission envelope coverage, especially for HLV.
Low development risk.	No escape capability for catastrophic failures during most of the proposed missions.
Orbital rescue involves capabilities already available or being developed for HVT vehicles for other reasons.	Pressure suit needed for emergency life support.
Low to moderate development risk for "soft" suit.	Requires a dedicated space rescue mission.
(Inflatable shelter can eliminate pressure suit requirement in orbit with low cost and risk.)	High development risk for total counter-pressure garment.
	"Soft" suit as encumbering as current pressure suits.
	(Inflatable shelters offer no pressure protection during atmospheric flight phases and require time to deploy and enter.)

- An inflatable shelter deployable from a special hatch near the crew station, also with a 12-hour life support capability;
- An HVT rescue pallet capable of being launched on two or three hours notice.

While this concept offers reduced weight and complexity over Concept 13, it has an even lower performance capability. There is no escape capability from above 315 KEAS or Mach 3 until stable orbit is achieved without operational control and thermal protection systems on the vehicle. Thus, the requirement of providing escape capability over the whole flight regime cannot be met, and this concept was not developed further.

4.15 CONCEPT 15 - EJECTION SEAT WITH INFLATABLE REENTRY CAPSULE

This concept is similar to the Concept 13 version with an inflatable shelter that was discussed in Section 4.13 except that in this case the inflatable device is capable of reentry on its own so that a rescue mission is not require. The system consists of:

- Basic escape Concept 2, an advanced, open ejection seat with Mach 3 capability;
- Basic escape Concept 6, an inflatable capsule with ablative outer layers to provide it with reentry capability;
- A tractor rocket type propulsion system to provide deorbit maneuver and separation capability for the reentry body;
- A capsule deployment hatch.

Escapes initiated at velocities below Mach 3 involve a more or less conventional seat ejection. All other flight phases require the crew to make the way to the deployment hatch, inflate and enter the reentry body, as described for Concept 13. After this, however, a tractor rocket is used to separate the capsule from the vehicle during the hypersonic/reentry flight phases or perform a deorbit maneuver during the orbital flight phase.

The capsule is based on the Orbital Escape System investigated by NASA during the 1960's which is described in the section on basic escape Concept 6. This design can be altered by the addition of the deployment hatch, discussed under Concept 13, which allows capsule deployment and use from within the vehicle and removes the need to don a pressure suit and exit the vehicle before deployment (Figure 4.6-1). This feature allows a much more rapid escape and eliminates the encumbrance of the suit.

Operation of the propulsion and cold gas attitude control systems could also be done under the control of a minicomputer instead of manually.

The referenced NASA system was a spherical design which would perform a ballistic reentry with no cross range capability. Goodyear, however, has conducted several studies of inflatable reentry bodies of other shapes which may allow the cross range capabilities desired for the HVT system. Because of the low weight of an inflatable system, it may be safer to attach the parachute system to the capsule itself instead of requiring the crewmember to extricate himself from the deflated structure while falling through the air. An impact attenuation bag could be made part of the inflatable structure.

Development requirements for this approach include:

- An ejection seat with a highly capable propulsion system;
- A double-layered, inflatable reentry body with ablative heat shielding and, probably, a hypersonic lifting body shape;
- A reentry body deployment hatch;
- A 12-hour emergency life support system;
- A digitally controlled, solid propellant, tractor rocket propulsion system and cold gas reaction control jets.

The advantages and disadvantages of this concept are listed in Table 4.15-1. The main problem with the concept is that escape capability may not be available for all flight conditions. The dynamic pressures during the high speed portion of the flight will be too high to deploy the capsule. While it may be possible to take the vehicle to a lower dynamic pressure environment by either losing speed or gaining altitude or, near the low end of the range, to protect the deployment hatch by increasing the vehicle's angle of attack, relying on being able to accomplish this after a major emergency would be extremely hazardous.

Another major problem is the time required and difficulty encountered in the crews' transferring to the deployment hatch and entering the capsule. The estimated 30 seconds may be too long in the event of a fire, and a control system failure may result in tumbling or gyration of the vehicle that would make the operation much more difficult.

In view of the above considerations, this concept is not expected to provide escape capability over the whole flight regime, and is not considered to be a viable option.

Table 4.15-1. Evaluation Of Escape Concept 15 – Ejection Seat With Inflatable Re-Entry Capsule

Advantages	Disadvantages
Moderate development risk.	Hypersonic escape not covered.
Minimal weight and design impact on the vehicle.	Capsule difficult to use under high accelerations or attitude rates.
Rescue mission not necessary.	Requires time to deploy and.enter capsule.
Pressure suit not necessary.	Integration of propulsion and other subsystems in the inflatable capsule may make the concept impractical.
Crossrange reentry capability possible.	

4.16 CONCEPT 16 - EJECTION SEAT WITH ROCKET-PACK TRANSFER TO RESCUE CAPSULE

The ejection seat system in this concept is the same as those used in Concepts 13 and 15. The orbital rescue approach is that described in basic escape concepts 10. Basic Concepts 8, and 9, mating with and rocket-pack escape to a space station, offer no advantage over a direct space rescue provided by Concept 10 and greatly increases the system's complexity.

Concept 16 consists of:

- o Basic Concept 2, an open ejection seat with Mach 3 capability,
- o An advanced, 8 psi pressure suit,
- o A system of orbital rescue capsules,
- o A rocket propulsion pack with the velocity change capability, enabling it to reach one of the rescue capsules, or
- o An emergency life support system with the capability needed to allow the crew to transfer to the rescue capsule.

As with Concepts 13 and 15, the crew uses ejection seats at speeds below Mach 3. In case of an emergency during the orbital flight phase, the crew, wearing pressure suits, leaves the vehicle with the rocket pack and life support system, which would probably be integrated into one unit and could be stored in the vehicle's payload bay. If necessary an orbital plane change maneuver is performed at the correct time to allow rendezvous with the most available rescue capsule. Once in the right orbital plane, the crew must wait until the right moment to enter an intercept orbit. For a 100 nm crew orbit and a 300 nm facility orbit this could involve a wait of over two days. At the appropriate time, the crew maneuvers into a transfer orbit to the altitude of the rescue capsule, circularize their orbit at that altitude with a second maneuver, then rendezvous with and enter it, abandoning their rocket pack. Once in the rescue capsule, the crew again has to wait until the appropriate time to fire the capsule's propulsion system to reenter and land in the continental United States.

Escape concept 16 requires:

- o An ejection seat with Mach 3 capability;
- o A minimally encumbering 8 psi pressure suit;
- o An emergency life support system capable of supporting the crew for as long as 55 hours; and,
- o An orbital rescue capsule with life support system, propulsion system, communications, reentry capability, and parachute recovery system.

The advantages and disadvantages of this concept are listed in Table 4.16-1. The major problem with this approach is the lack of escape capability for the upper atmospheric hypervelocity and reentry flight phases. Thus, the concept doesn't provide the desired escape capability for the vehicles' entire performance envelope, and is not considered as a viable option for HVT escape system.

Table 4.16-1. Evaluation Of Escape Conce. 16 – Ejection Seat With Rocket Pack Transfer To Rescue Vehicle

Advantages	Disadvantages
Ejection seats have small weight and design impact on the vehicle.	No escape capability for hypersonic and reentry flight.
Moderate development risk for rescue capsule.	Very large rescue capsule system deployment and logistics cost.
Does not require rescue mission.	Pressure suit needed for emergencies.
	Rocket pack will be heavy and bulky.
	Requires crew to wear pressure suits for as long as 2 days.
	Requires very large emergency life support system.

5.0 SELECTED ESCAPE CONCEPTS DEVELOPMENT AND OPERATION

As discussed in Section 4.0, a preliminary evaluation of 16 escape concepts showed that only 3 of these concepts are viable candidates for providing emergency crew escape over the whole flight regime of the hypervelocity vehicles being considered. These 3 concepts are:

- o Encapsulated seat with thermal protection
- o Separable nose capsule with thermal protection
- o Pod-type capsule with thermal protection

As may be noted from their description in Sections 4.4 and 4.5, the last two concepts, i.e., the separable nose capsule and the pod-type capsule are very similar to each other. The main difference is that while the whole forebody of the vehicle is separated to form the nose capsule, only part of the crew cabin is separated to form the pod-type capsule. Corresponding, the pod-type capsule tends to be lighter than the nose capsule, although it does have a more complex separation mechanism. For a typical airplane, either one of the two may be a better choice than the other, depending upon various design considerations. However, an examination of both the HLV (Figure 2.1-2) and the VLV (Figure 2.1-4) indicates that both these vehicles have very long noses, which will tend to make the pod-type capsule decidedly better than the nose capsule. The cabin of the VLV orbiter is aft of a 60-foot hydrogen tank so that a forebody would comprise about two-thirds of the vehicle. The cabin is also far aft on the long-nosed HLV. By moving the crew closer together (making seat access more difficult) and rearranging avionics and reaction control systems, the cabin could be moved forward to shorten the forebody somewhat. Tapering the nose more quickly (which would change the vehicle's aerodynamics) or going to a smaller one-man crew would allow an even shorter capsule length. However, these vehicle configuration options are not available to the escape system designer. The detailed design development need, therefore, be done only for the pod-type capsule, and not for both types of capsules.

The development and operation of the encapsulated seat design is discussed in Sections 5.1 and 5.2 for the HLV and the VLV respectively. Similar description of the pod-type capsule design is provided in Sections 5.3 and 5.4 for the HLV and the VLV respectively.

5.1 ENCAPSULATED SEAT FOR HORIZONTALLY LAUNCHED VEHICLE

5.1.1 Design Description

An advanced encapsulated seat design for hypervelocity vehicles has been developed and is shown in Figure 5.1-1. The front view of 2-place side-by-side version of this seat, suitable for the horizontally launched vehicle, is shown in Figure 5.1-2.

The design consists of an aerodynamically shaped outer shell constructed of a lightweight, heat resistant material such as reinforced carbon-carbon (RCC) composite containing the crew seats and subsystems and covered with a carbon-phenolic ablative coating where required. The open upper part of the shell gives the crew access to the vehicle controls and displays and improved external vision. Unlike previous encapsulated seat designs, however, the shell is integrated with the vehicle control panels with the lower edge of the opening at the level of the bottom of the displays. The crews' feet are always within the shell and do not have to be retracted prior to ejection. Primary fly-by-wire controls such as control stick, throttles, rudder pedals and key pad are mounted inside the capsule and can be used to control the vehicle while the seat door is closed. This feature allows the crew to dispense with pressure suits since a cabin depressurization automatically triggers closure of the capsule door and starts the emergency life support system.

The door itself is an airtight fabric, such as polyurethane-coated Kevlar, for lighter weight and smaller stowage volume than a segmented solid door. A soft door requires ribs or stays in addition to its internal pressurization to stiffen it against aerodynamic forces during high Q ejections and a thermal blanket of a material similar to Nicalon for protection against dynamic heating. A small heat resistant window is included to allow a view of displays through the closed door. A powered reel closes the door and may also be used to operate an arm capture mechanism to prevent crew members' arms from jamming the door.

A propulsion module is mounted to the heat shield by separable, heat resistant straps. A variable-thrust gelled propellant rocket with thrust vectoring capability for pitch control is provided. Unlike past encapsulated seat designs, this rocket serves the purpose of getting away from the vehicle in atmospheric flight as well as acting as a retrorocket for the deorbit maneuver during orbital escape. A capability of 430 ft/sec velocity change is sufficient to provide both of these functions.

During atmospheric flight, the rocket system provides a separation from the vehicle after the catapult stroke, stabilization and deceleration control during the period of highest dynamic pressure. Since this will always occur at suborbital velocities and altitudes, a deorbit maneuver is not necessary. During orbital flight, there are no

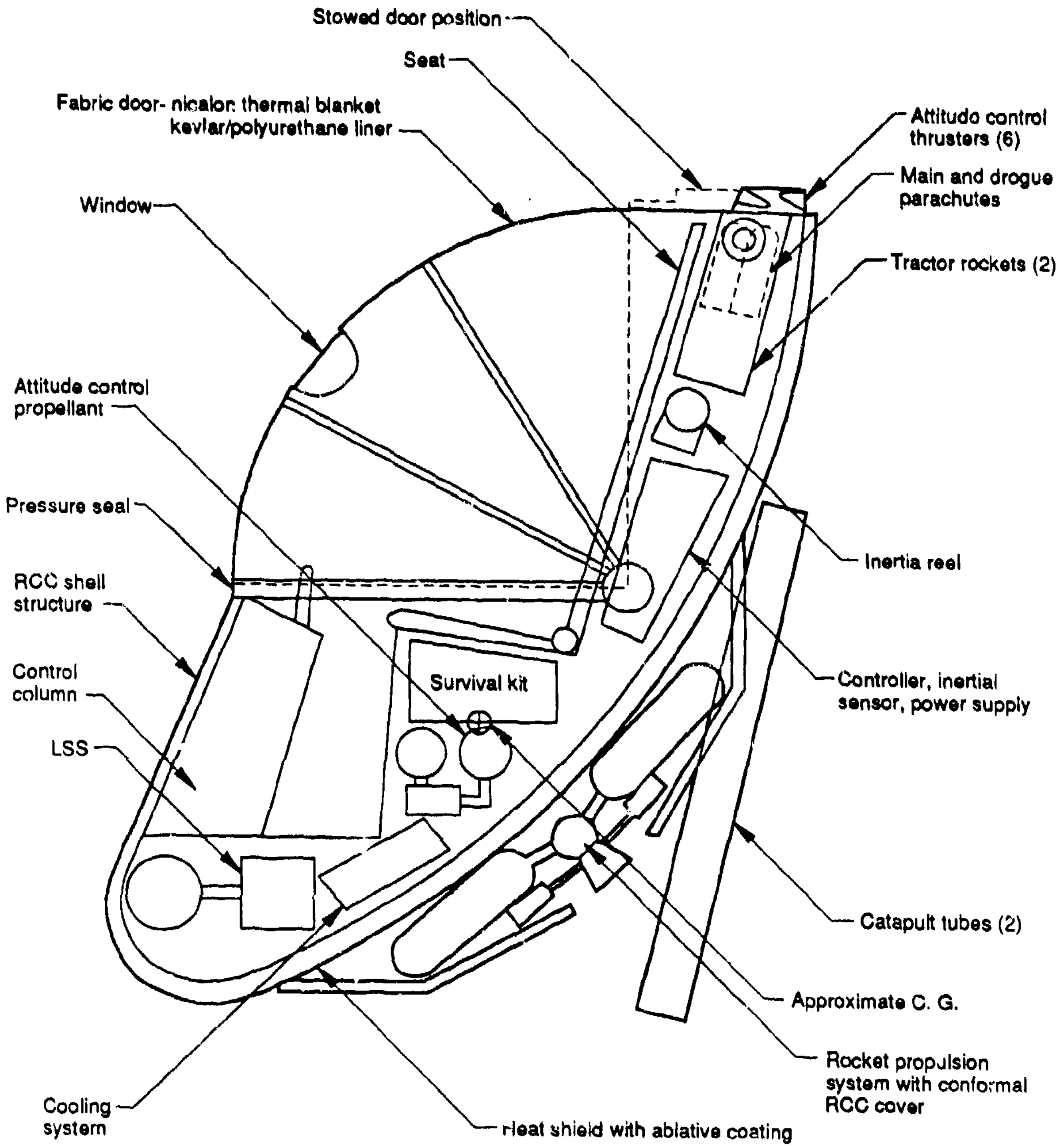
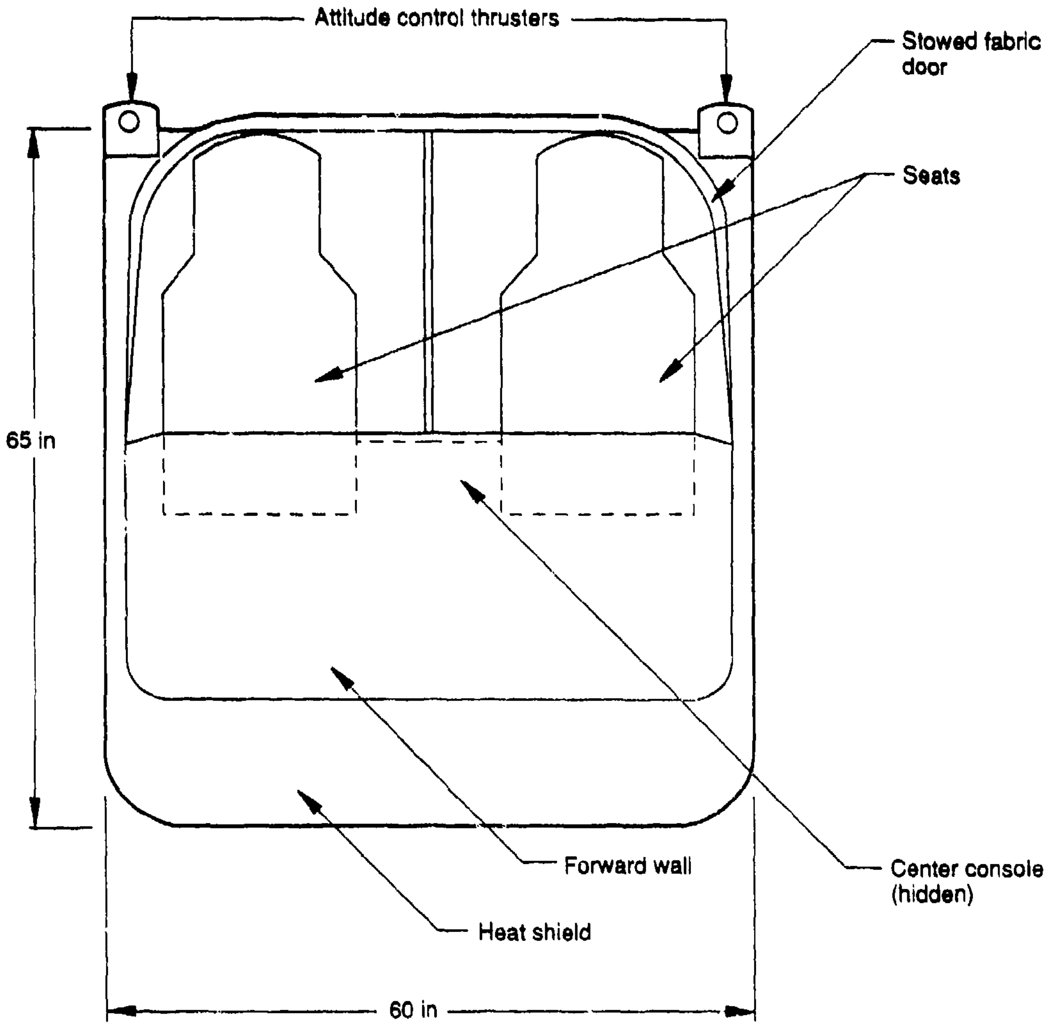


Figure 5.1-1. Encapsulated Seat Design for Hypervelocity Vehicles



- Side view similar to single place seat
- Catapult and propulsion module in rear

Figure 5.1-2. Front View of 2-Place Encapsulated Seat

dynamic forces on the vehicle and the catapult provides all the separation velocity required. At the desired deorbit point, the encapsulated seat is oriented with the propulsion thrust vector forward. The propulsion module is jettisoned after the deorbit maneuver is completed. Since the seat can assume any needed attitude for the deorbit maneuver, propulsion module location and thrust vector orientation are dictated by vehicle separation and atmospheric escape considerations.

During main propulsion system firing, trajectory and pitch control is accomplished by varying thrust and by thrust vector control. The main nozzles are supplemented by an internal attitude control system (ACS) with six 125 to 1250 pound variable thrust, gelled propellant rocket motors mounted in two pads on the upper corners of the heat shield (see Figures 5.1-1 and 5.1-2). The ACS would be used primarily to provide stability, to orient the capsule for the deorbit maneuver and to direct its lift vector in other escape conditions.

The maximum dynamic pressure encountered by the HLV is 2000 psf during ascent. In order to ensure that the maximum crewmember acceleration limits are satisfied during ejection at this high dynamic pressure, it is essential that the heat shield drag area be kept low. A rectangular heat shield instead of a circular heat shield (Figure 5.1-2) has been selected to achieve the desired low drag area without compromising thermal protection of the seat.

Due to its location at the back of the seat, the heat shield will not be facing the apparent wind vector immediately after ejection. Thus, a pitch maneuver is performed at ejection during hypersonic flight to position the heat shield forward. The front seat structure materials are designed to withstand the high heating rates during the first few seconds after ejection.

The lift required to achieve the crossrange capability is achieved by pitching to an angle of attack, which provides a good L/D. As shown in Figure 5.1-1, the encapsulated seat design includes life support system, recovery and drogue parachutes, restraint system, digital controller with associated power supply, sensors, catapult tubes, survival kit and other typical ejection seat components.

Unlike previous encapsulated seats, the crew does not land in the seat, but the door is pyrotechnically separated and the crew extracted and recovered by their personal parachutes.

5.1.2 Escape Sequencing and Operation

The emergency escape is initiated by a crewmember pulling an escape handle, which is similar to that on a conventional ejection seat. This initiates the digital controller/sequencer (which is constantly powered) and sends appropriate pyrotechnic signals to cause the following events.

1. Evaluate escape condition based on information from the vehicle data bus and seat-mounted sensors, and conduct life threat assessment. (start at 0.010 second, complete at 0.020 second after initiation)
2. Initiate thermal batteries for internal seat electrical power. (0.010 second start, 0.050 second complete)
3. Initiate haulback devices to position crew member for ejection. (0.030 second start, 0.200 second complete)
4. Initiate limb capture devices to prevent jamming of seat door. (0.030 second start, 0.200 second complete)
5. Close and lock seat door. (0.200 second start, 0.250 second complete)
6. Initiate seat oxygen and pressurization system. (0.250 second)
7. Jettison ejection hatch. (0.250 second start, 0.300 second complete)
8. Initiate catapult. (0.300 second)

The subsequent events depend upon the flight condition at escape. For escape during atmospheric flight below Mach 3, including zero/zero:

9a. The propulsion system fires immediately after the catapult stroke, separating the seat from the vehicle, stabilizing it, steering to avoid ground impact and providing the gentlest deceleration possible at higher dynamic pressures. (about 0.5 second).

10a. If the airspeed is between 300 and 500 KEAS, the drogue is deployed to further decelerate the seat and stabilize it in a feet-forward position.

11a. When the airspeed is below 300 KEAS and the altitude is below 15,000 feet, the main recovery parachute is deployed and the fabric door and drogue are jettisoned.

12a. The restraints are then severed allowing the parachute to remove the crewmember and his survival kit from the seat similar to current ejection seats.

13a. The crew member then makes a conventional parachute landing and awaits recovery.

For escape during hypersonic flight, including reentry (Figure 5.1-3)

9b. The propulsion system again fires immediately after the catapult stroke, separating the seat from the vehicle and using thrust vector control to pitch the seat in order

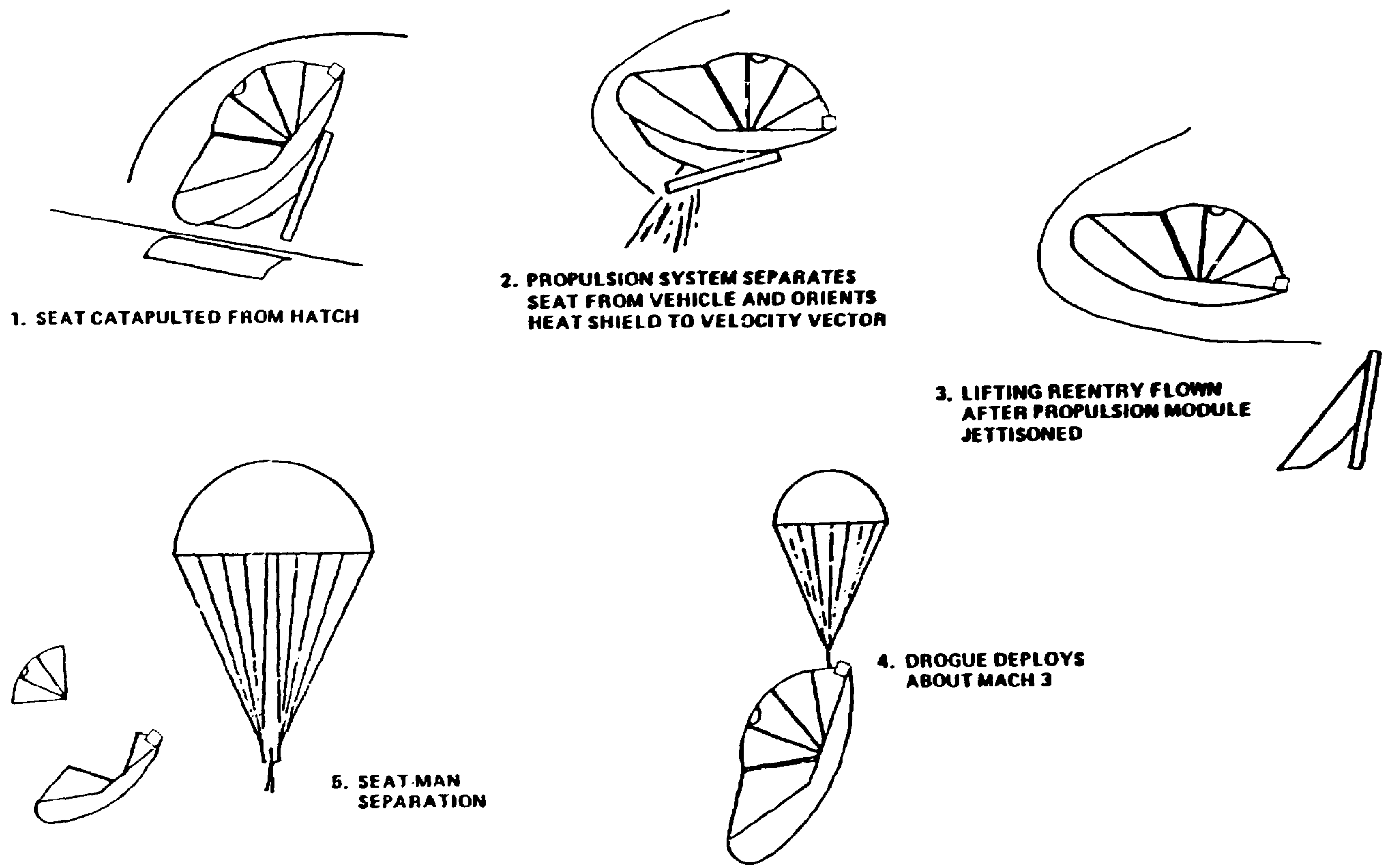


Figure 5.1-3. Encapsulated Seat Escape Sequence (Hypersonic/Reentry Flight Phase)

to position the heat shield forward to protect the fabric door from aerodynamic heating (at 0.5 second)

10b. The propulsion module is jettisoned (at 1.5 second)

11b. Using its inertial sensing unit and attitude control thrusters, the seat orients its body lift vector to control the aerodynamic heating rate and provide cross-range capability. (1.5 second - 20 minutes)

12b. After the velocity drops below Mach 3, the sequence follows the same pattern as the phases described earlier in steps 10a through 13a.

For escape during orbital flight:

9c. After being catapulted free of the vehicle, the seat orbits with a slow rotation to reduce solar heating until an automatic control command or a manual command from the crewmember sets the time for the deorbit maneuver for a landing in the continental United States. (0.5 second - 6 hours)

10c. The attitude control thrusters orient the seat for the deorbit maneuver. (lasts about 10 seconds)

11c. The propulsion system performs the deorbit maneuver using low thrust levels (lasts about 2.0 seconds). Note that if the emergency occurs in suborbit, the propulsion system can be used to select the best possible landing point.

12c. The heat shield is positioned forward.

13c. The sequence now follows the same pattern as the hypersonic flight escape sequence beginning with step 10b.

5.2 ENCAPSULATED SEAT FOR VERTICALLY LAUNCHED VEHICLE

5.2.1 Design Description

The encapsulated seat design for the vertically launched vehicle is similar to that for the horizontally launched vehicle discussed in Section 5.1.1, except for the following differences:

a. The VLV encapsulated seat is designed to accommodate 1 person compared with 2 persons for the HLV.

b. Some of the design details, such as thickness of ablative coating and attitude control system capability, is different because of the differences in maximum dynamic pressure (400 psf for VLV compared with 2000 psf for HLV), aerodynamic drag area, and system ejected weight.

The sideview of the encapsulated seat for VLV is similar to that for HLV and is shown in Figure 5.1-1. The front view of the single place encapsulated seat for VLV is shown in Figure 5.2-1.

The various subsystem locations and their operation for the VLV encapsulated seat are similar to those described for the HLV encapsulated seat in Section 5.1.1.

5.2.2 Escape Sequencing and Operation

The escape sequencing and operation for the VLV encapsulated seat is the same as described for the HLV encapsulated seat in Section 5.1.2.

5.3 POD-TYPE CAPSULE FOR HORIZONTALLY LAUNCHED VEHICLE

5.3.1 Design Description

The pod-type capsule shares its basic structure with the crew cabin, as shown in Figure 5.3-1. It is designed to separate from the vehicle at ejection initiation, and bring the crewmembers back to earth meeting all the escape and crew protection requirements. A side view of the capsule, together with its components, is shown in Figure 5.3-2. The salient features of the design are discussed below.

The front part of the capsule is a conical/hemispherical heat shield made of Reinforced Carbon-Carbon (RCC) or Advanced Carbon-Carbon (ACC) together with an ablative material coating. An ablative carbon phenolic coating is provided on the bottom of the capsule. The top of the capsule is part of the normal vehicle structure exposed to high temperature environment and is made of high temperature material. No changes are expected to be made to this structure. The crew cabin will remain as an enclosed area and can provide a shirt sleeve environment even during escape.

Special blow away panels are provided on the top of the front heat shield to facilitate clean separation of the capsule from the vehicle and yet provide the desired conical/hemispherical shape of the capsule heat shield.

Folding wings are provided to increase crossrange capability for escape during high atmosphere flight (Figure 5.3-3). These wings are normally stowed in a retracted position along the side and bottom of the capsule. These are deployed soon after ejection to achieve a lift to drag ratio of about 0.8. The desired cross range is then achieved by rolling the escape capsule to generate sideward force, as is done in a conventional airplane. Some additional cross range can be generated by adjusting capsule pitch angle to modify lift and drag, and by using on-board propulsion capability.

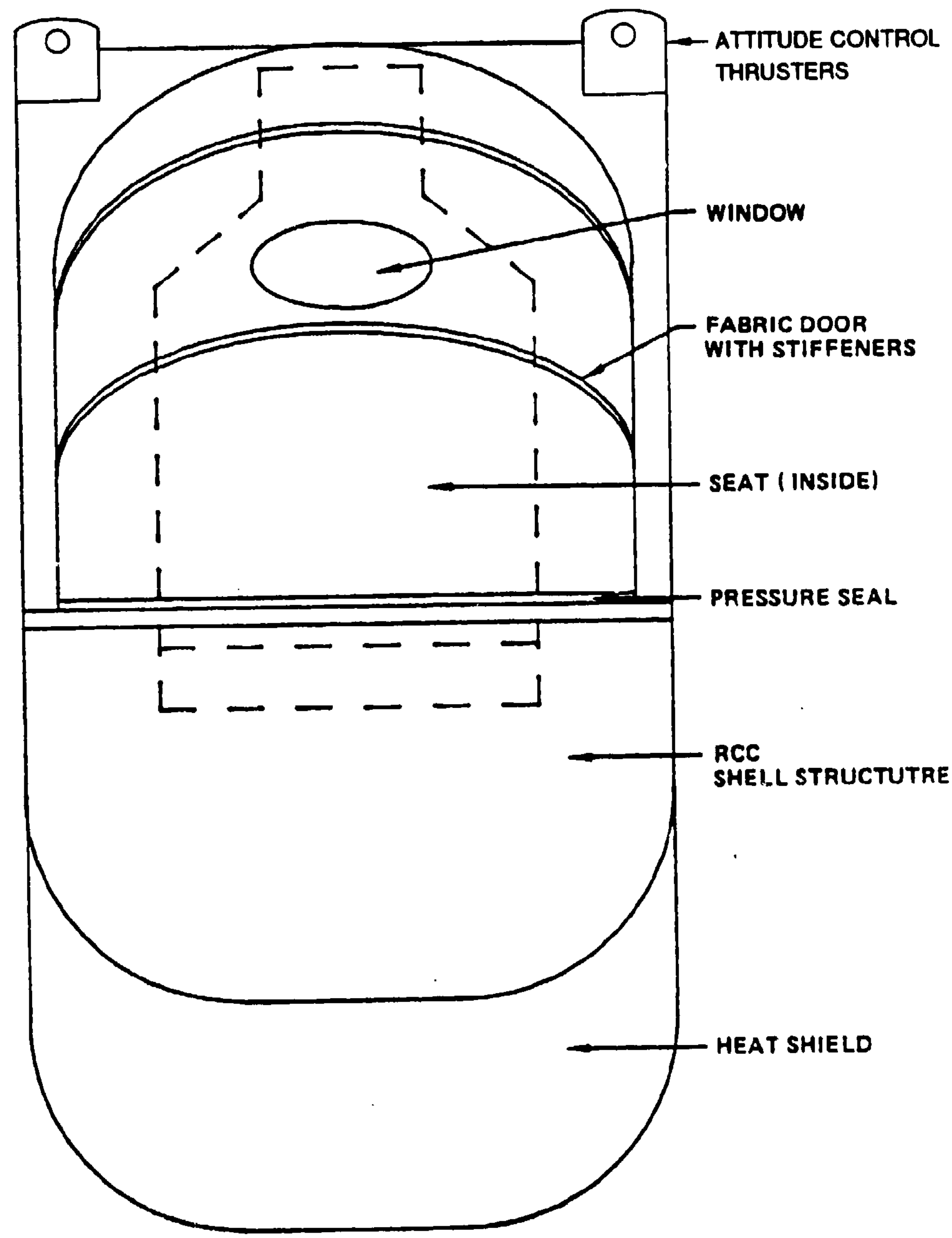


Figure 5.2-1. Front View of Single Place Encapsulated Seat

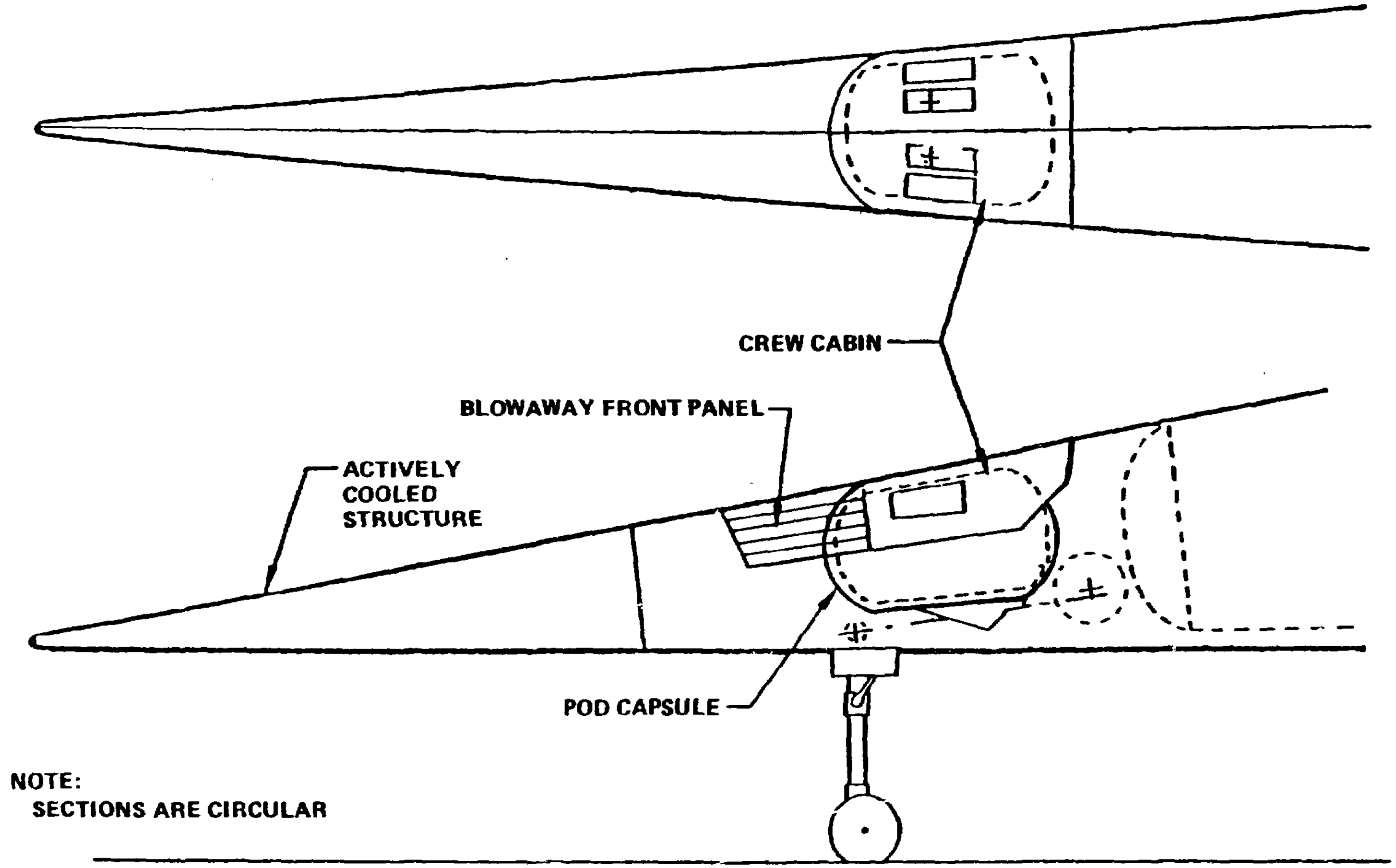


Figure 5.3-1. Location of the Pod Capsule in Horizontally-Launched HVT Vehicle

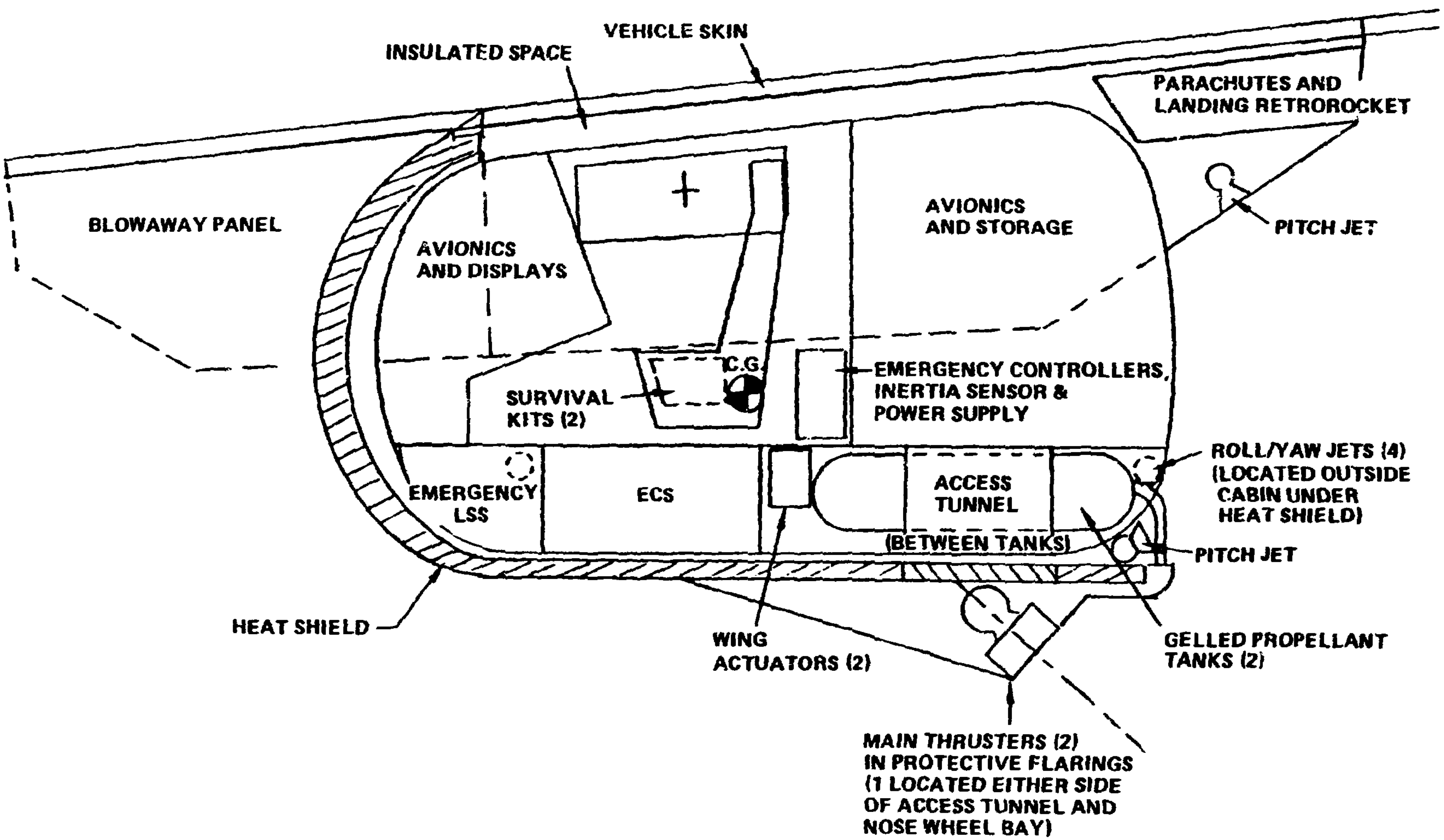


Figure 5.3-2. Pod-Type Capsule for Horizontally-Launched Hypervelocity Vehicle

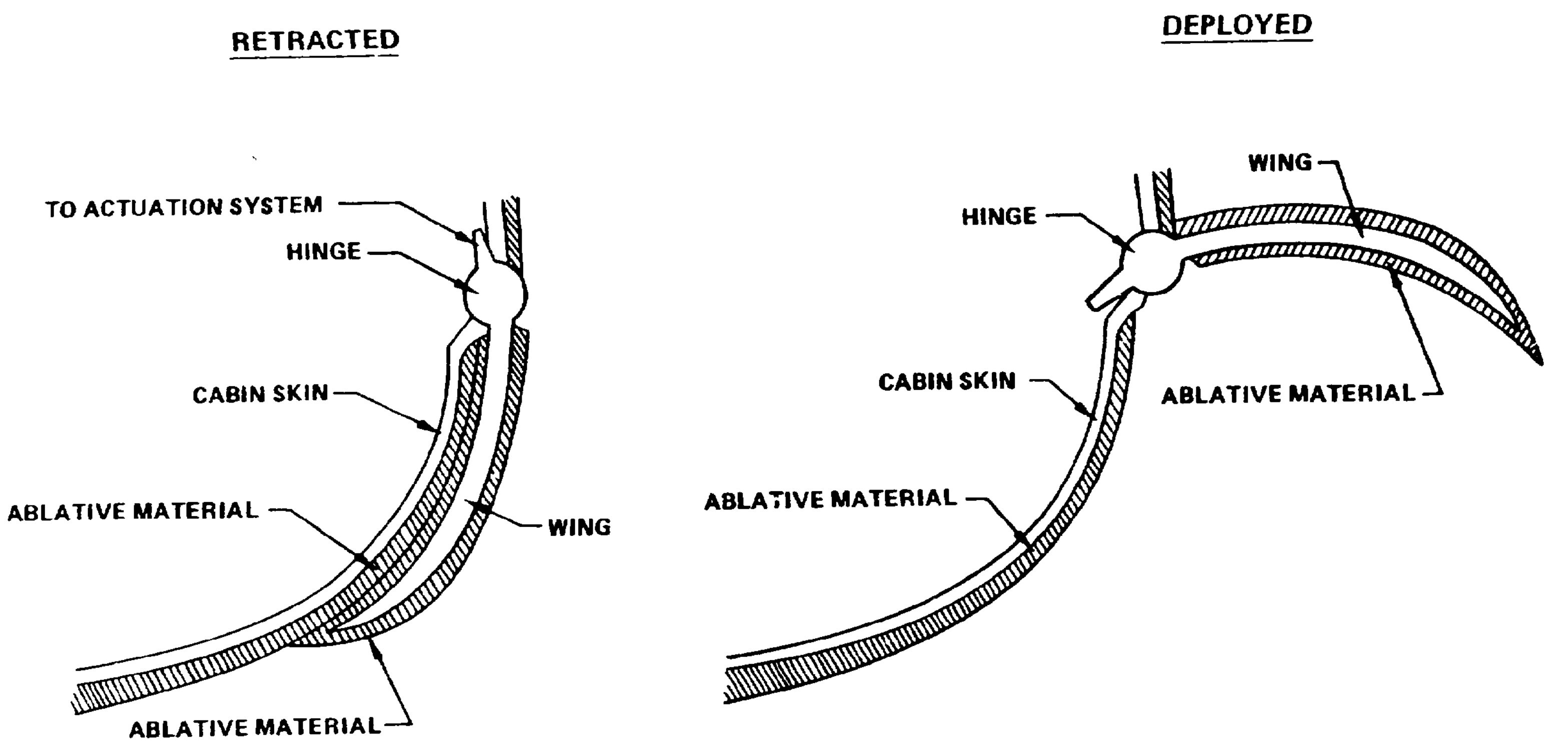


Figure 5.3-3. Pod Capsule Wings in Retracted and Deployed Positions

The propulsion system has selectable thrust nozzles with thrust vectoring capability in pitch for trajectory control as well as reaction jets for attitude control. Use of gelled propellants will help minimize the weight of the propulsion system. The thruster nozzles are used for separation from the vehicle, trajectory control in atmospheric flight, and as a retrorocket for the deorbit maneuver during orbital escape. A capability of about 430 ft/sec velocity change will be sufficient to provide all of these functions.

It should be noted that the maximum propulsion capability is not the sum of that required for escape during atmospheric flight and that for escape during orbital flight. For escape during atmospheric flight, propulsion is required not only for separation, but also for deceleration control under high dynamic pressures, and trajectory control to get away from ground and vehicle. For escape during orbital flight, an additional deorbit maneuver is required, but no thrust is required for trajectory control to get away from ground or for deceleration control at high dynamic pressures.

An emergency life support system provides the required oxygen, cooling and pressurization for the crewmembers. It is sized to provide life support capability for 6 hours to allow selecting appropriate deorbit time for landing in continental United States during orbital escape.

As shown in Figure 5.3-2, the pod capsule design also includes other typical advanced capsule subsystems, such as recovery and drogue parachutes, restraint system, digital controller with associated power supply, sensors, and flotation system.

5.3.2 Escape Sequencing and Operation

The emergency escape sequence is initiated by a crewmember pulling an escape handle, which is similar to that used on the F-111 escape module. This initiates the digital controller/sequencer (which is constantly powered) and sends appropriate pyrotechnic signals to cause the following events:

1. Evaluate escape condition based on information from the vehicle data and pod-mounted sensors (start at 0.010 second, complete at 0.020 second after initiation)
2. Initiate thermal batteries for internal capsule electrical power. (0.010 second start, 0.050 second complete)
3. Initiate haulback devices to position crew member for ejection. (0.030 second start, 0.200 second complete)
4. Initiate capsule emergency oxygen and pressurization. (0.030 second)
5. Pyrotechnically severe the capsule structural supports, blow-out skin panels and vehicle system connections. (0.050 second)

6. Initiate propulsion system to separate the pod from the vehicle. (0.2 second start, 0.4 second end)

The subsequent events depend upon the flight condition at escape. For escape during atmospheric flight at speeds below Mach 3, the following steps are followed:

7a. The propulsion system continues to provide thrust, stabilizing the capsule, steering to avoid ground impact and controlling deceleration at higher dynamic pressures. (0.4 second start, 1.2 seconds end)

8a. After propulsion system shutdown, the drogue is deployed to stabilize and decelerate the capsule (except at low speeds and altitudes, where recovery parachute may be deployed directly). When the pod speed and altitude fall below 300 KEAS and 15,000 feet respectively, or during low speed low altitude escapes, when the desired altitude above ground level has been achieved, the recovery parachute is deployed to achieve a terminal sink rate of 30 ft/sec.

9a. As the capsule approaches the ground under the recovery parachute, retrorockets are initiated to reduce the sink rate to less than 10 ft/second at ground impact.

For escape during hypersonic flight, including reentry, the following steps are followed (Figure 5.3-4).

7b. The propulsion system continues to provide thrust, stabilizing the flight, providing low deceleration and rolling the capsule as required for cross range. (0.4 - 1.2 seconds)

8b. The folded wings are deployed to increase the lift to drag ratio. Also, the main nozzles are jettisoned. (1.2 seconds)

9b. The pod attitude control system is used to orient the lift vector for the desired deceleration profile and cross range maneuvering. (up to 20 minutes)

10b. When the pod velocity drops below Mach 3, the sequence follows the pattern described earlier beginning with step 8a.

For escape during orbital flight, the following steps are followed:

7c. The pod remains in orbit with a slow rotation to reduce solar heating and conserve propellant until a command from the automatic control system or the crew member selects the time for the deorbit maneuver. (0.5 second - 6 hours)

8c. The attitude control thrusters orient the pod for the deorbit maneuver. (lasts about 10 seconds)

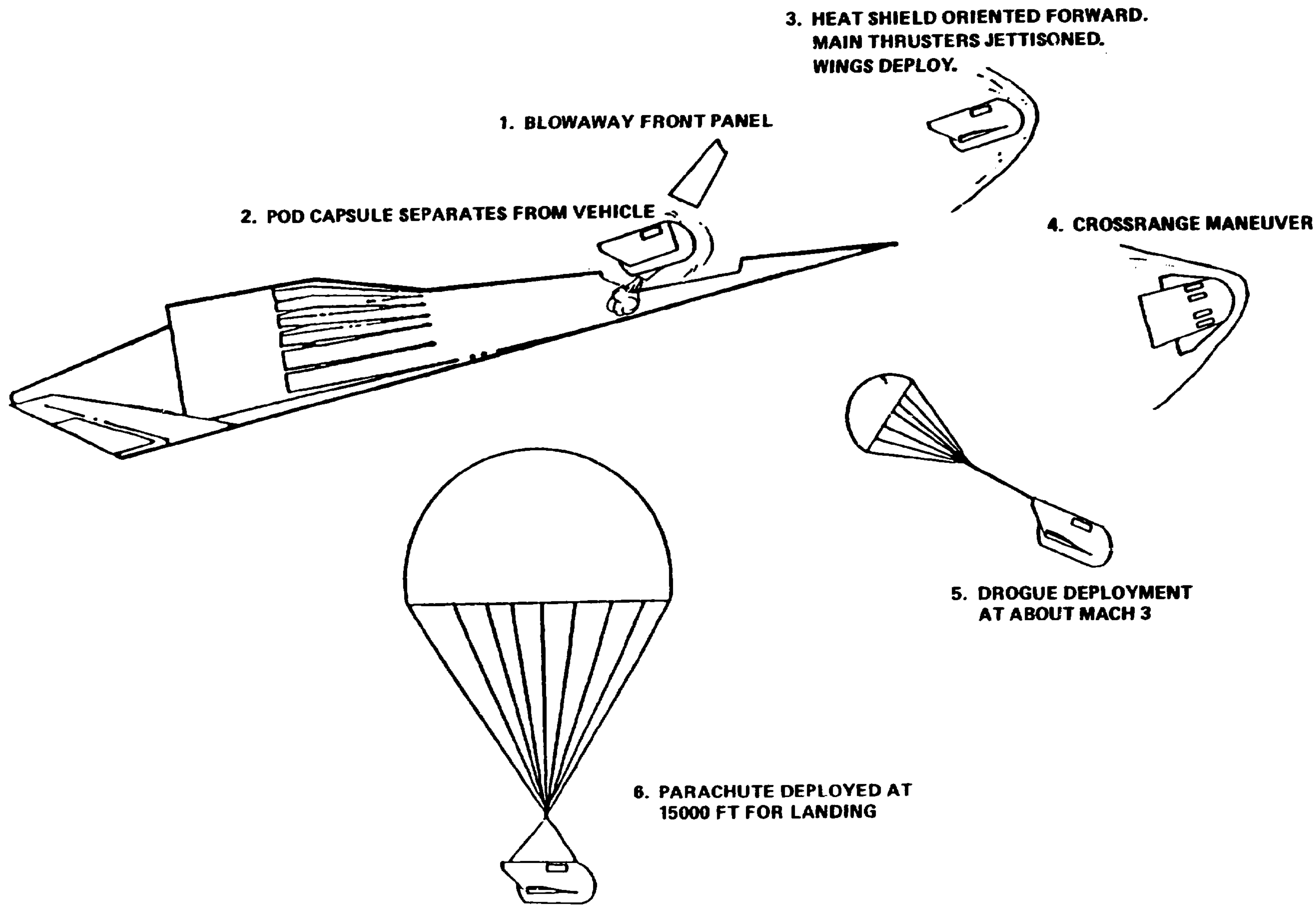


Figure 5.3-4. Escape Sequence for HLV Pod Capsule During Upper Atmospheric Escape

9c. The propulsion system performs the deorbit maneuver using low thrust levels (lasts about 2.0 s). Note that if the ejection occurs in suborbit, the propulsion system can be used to select the best possible landing point.

10c. At atmospheric reentry, attitude control thrusters are used to reorient the pod to bring the heat shield in the forward-facing position.

11c. The sequence now follows the same pattern as the hypersonic flight escape sequence beginning with step 7b.

5.4 POD-TYPE FOR VERTICALLY LAUNCHED VEHICLE

5.4.1 Design Description

The pod-type capsule for the vertically launched vehicle has been developed by modifying its crew cabin, as illustrated in Figures 5.4-1 and 5.4-2. The location of the various subsystems and components is also shown in Figure 5.4-2. This capsule is described below as a hybrid capsule, with an extraction system used for recovery and landing of the crewmember.

The salient features for the capsule design include:

- Separable cabin structure with two support/separation guidance rails, linear shaped charge (LSC) severable cabin supports and skin panels, Environmental Control System (ECS) and electrical lead severance using LSC cutter assemblies
- A large, dedicated, emergency heat shield
- A rocket propulsion system, using gelled hypergolic fuels, capable of removing the rescue pod safely away from the vehicle during any flight phase including off-the-pad aborts and flight at maximum dynamic pressure (Q), and of performing a deorbit maneuver after separation while in orbit.
- An emergency life support system capable of sustaining the crew while in orbit and during reentry until a landing in the continental United States is possible
- An attitude control system, using similar gelled propellants, for stabilization during atmospheric escapes, orienting the pod for the deorbit maneuver, and control during reentry
- A drogue parachute to stabilize and decelerate the pod at lower velocities
- A tractor rocket and personal parachute to remove the crewmember from the pod prior to landing impact, and
- Survival equipment appropriate for land or water rescue in any part of the world.

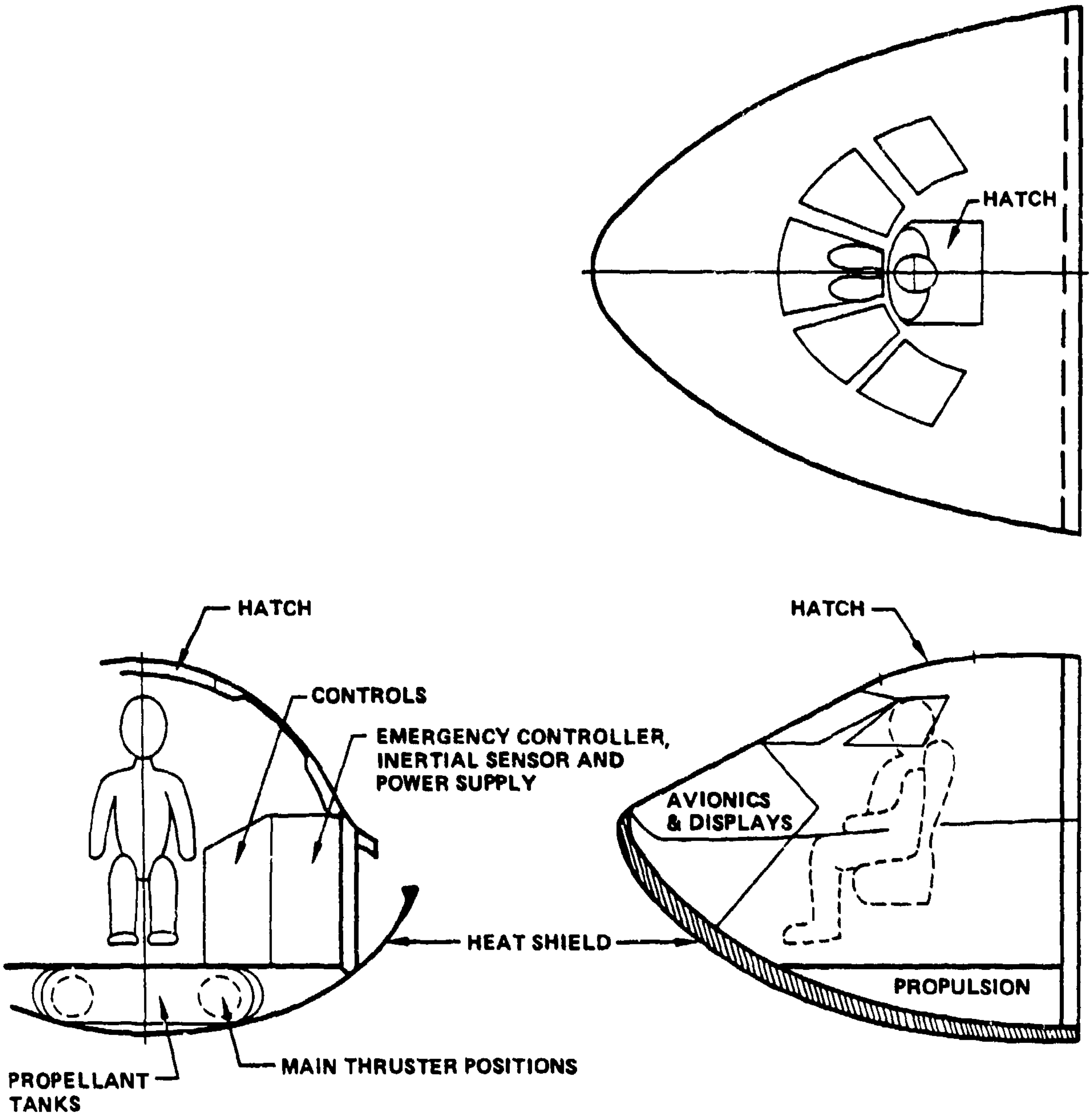


Figure 5.4-1. Vertically-Launched Vehicle Escape Pod External Configuration

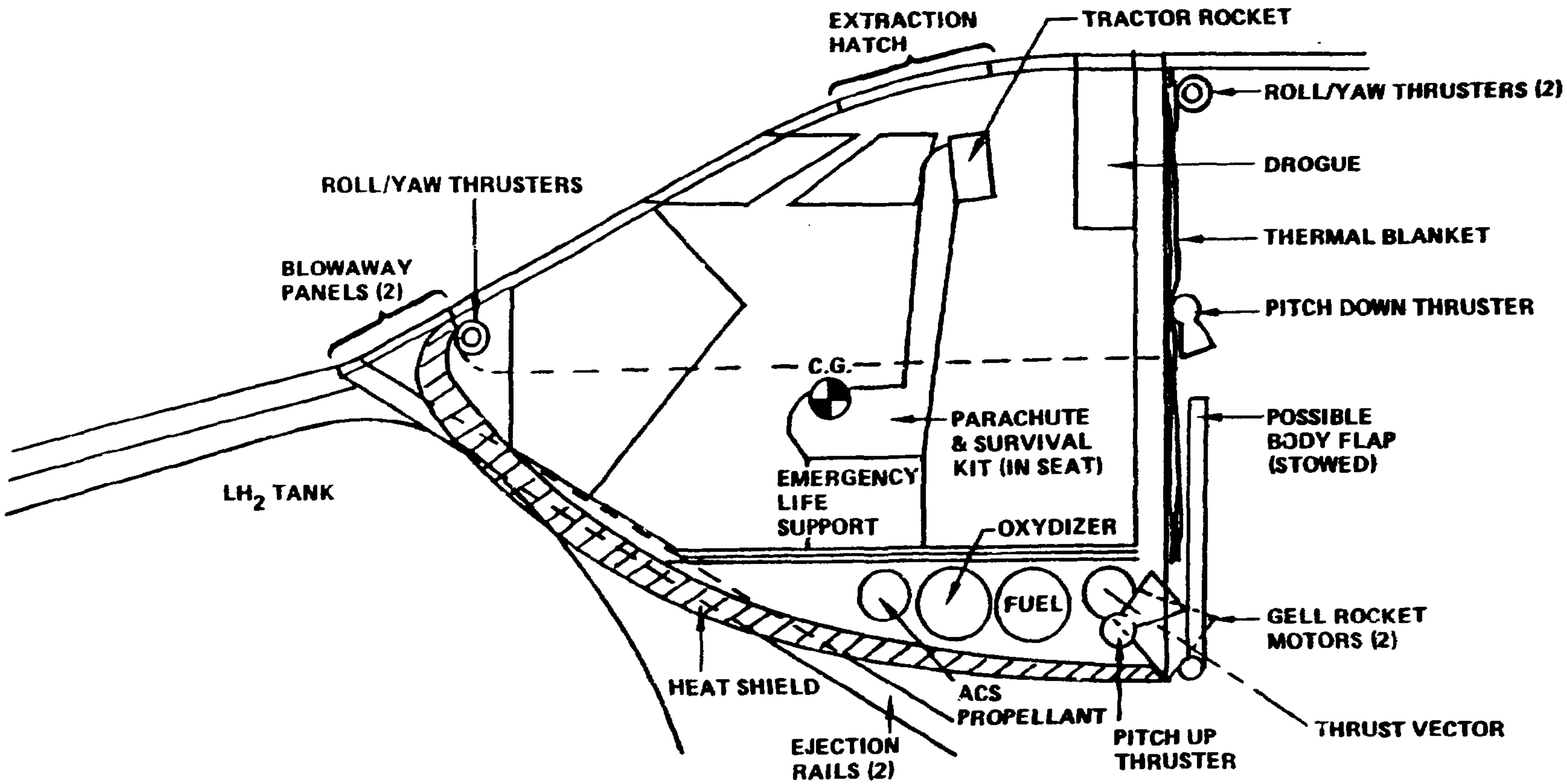


Figure 5.4-2. Vertically-Launched Vehicle Pod Capsule Configuration and Subsystems

The general configuration of the pod is a blunt, rounded cone, slightly flattened on the bottom for a greater lift to drag (L/D) ratio during reentry. There is also the possibility of adding a deployable body flap to the aft end of the pod to increase the L/D for enhanced cross range capability. The body flap, and the heat shield itself, would be made of RCC with an ablative coating. The aft wall of the pod, facing the payload bay, is insulated with thermal blankets. The capsule's center of gravity (C.G.) is placed to stabilize it aerodynamically with the heat shield facing the velocity vector. The body lift vector is controlled during reentry by rotating the pod with the ACS.

To avoid passing the main thruster through the heat shield and to allow the most vertical escape possible from the launch pad, the main thrust vector is located at the lower aft edge at about 55 degree to the aft plane. To prevent possible interference with the vehicle during separation, the pod slides on two aluminum rails, mounted parallel to the thrust vector, on six Teflon coated slipper blocks attached to the outside of the heat shield (Figure 5.4-3). The rails also form part of the pod support structure during normal flight operations.

The heat shield is slightly larger than the crew cabin, and the gap between the two, normally covered by skin panels, accommodates the pod's electrical, ECS, and remaining structural interfaces with the rest of the vehicle, as shown in Figure 5.4-3. At separation, the panels, structure and other interfaces are severed by LSC and the panels are pushed aside as the pod accelerates up the rails. Once clear of the vehicle, the pod can modify its trajectory as required by the escape conditions.

The ACS yaw thrusters are mounted just above the edge of the heat shield on the nose of the pod. All other ACS thrusters are on the aft bulkhead.

The crew extraction system, including tractor rocket and parachute, is similar to the Stanley Yankee system, now marketed by UPCO. The emergency life support system is located in the cabin under the side panels.

5.4.2 Escape Sequencing and Operations

The emergency escape sequence is similar to that for the pod capsule for the HLV. It is initiated by a crewmember pulling an escape handle, which is similar to that used on the F-111 escape module. This initiates the digital controller/sequencer (which is constantly powered) and sends appropriate pyrotechnic signals, to cause the following events:

1. Evaluate escape condition based on information from the vehicle data and pod-mounted sensors (start at 0.010 second, complete at 0.020 second after initiation)

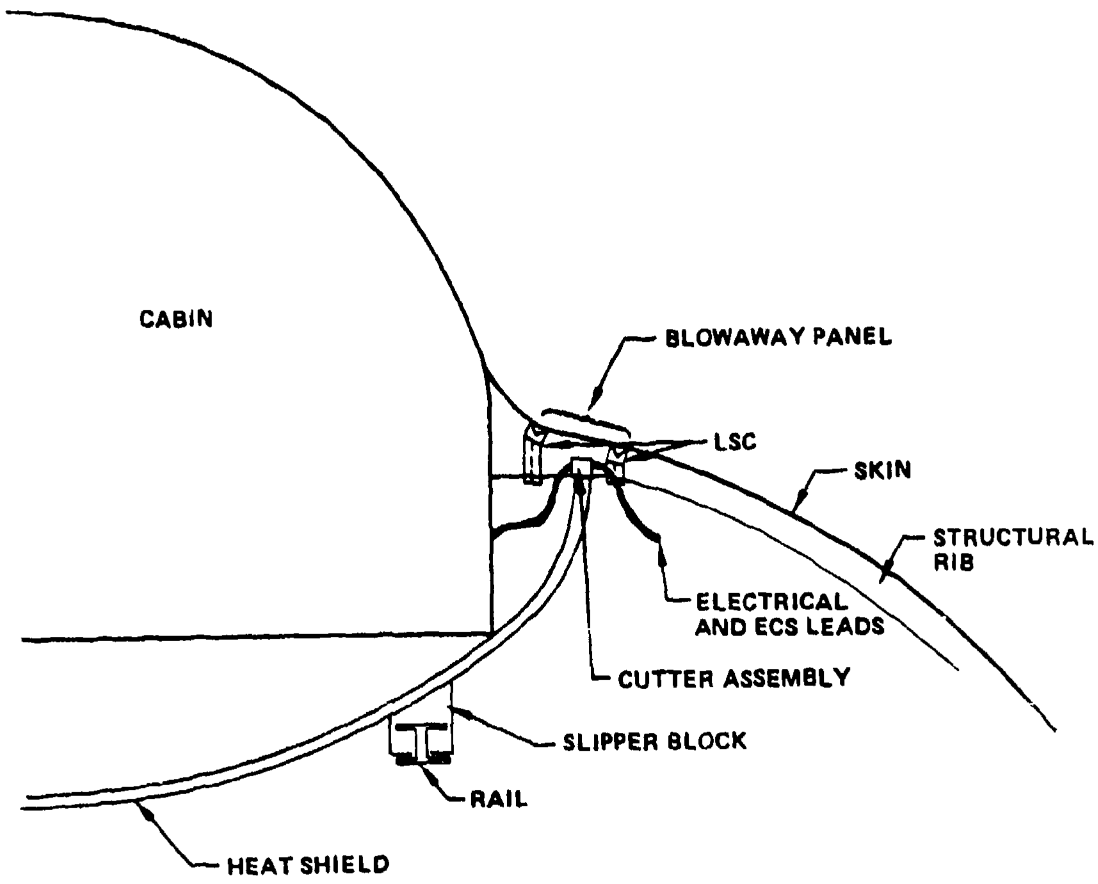


Figure 5.4-3. Pod Capsule Severence Details for Vertically-Launched Vehicle

2. Initiate thermal batteries for internal capsule electrical power. (0.010 second start, 0.050 second complete)
3. Initiate haulback devices to position crew member for ejection. (0.030 second start, 0.200 second complete)
4. Initiate capsule emergency oxygen and pressurization. (0.030 second)
5. Pyrotechnically sever the capsule structural supports, blow-out skin panels and vehicle system connections. (0.050 second)
6. Initiate propulsion system to separate the pod from the vehicle (0.2 second start, 0.4 second end)

The subsequent events depend upon the flight condition at escape. For escape during atmospheric flight at speeds below Mach 3, the following steps are followed:

7a. The propulsion system continues to provide thrust stabilizing flight, steering to avoid ground impact and providing low deceleration at higher dynamic pressures. (0.4 second start, 1.2 seconds end)

8a. After propulsion system shutdown, the drogue is deployed to stabilize and decelerate the capsule (except at low speeds and altitudes, where the extraction system may be immediately used). When the pod speed and altitude fall below 300 KEAS and 15,000 feet respectively, or during low speed low altitude escapes, when desired altitude above ground has been achieved, the ejection hatch is jettisoned.

9a. The tractor rocket is fired and the crew restraint system is released allowing the crewmember to be pulled through the ejection hatch by his parachute harness. A static line deploys the recovery parachute as soon as he leaves the capsule.

10a. The crewmember then makes a conventional parachute landing and awaits recovery.

For escape during hypersonic flight, including reentry, the following steps are followed (Figure 5.4-4).

7b. The propulsion system continues to provide thrust, stabilizing the capsule, controlling deceleration and rolling the capsule as required for cross range. (0.4 - 1.2 seconds)

8b. The pod attitude control system is used to orient the lift vector for the desired deceleration profile and cross range maneuvering. (up to 20 minutes)

9b. When the pod velocity drops below Mach 3, the sequence follows the pattern described earlier beginning with step 8a.

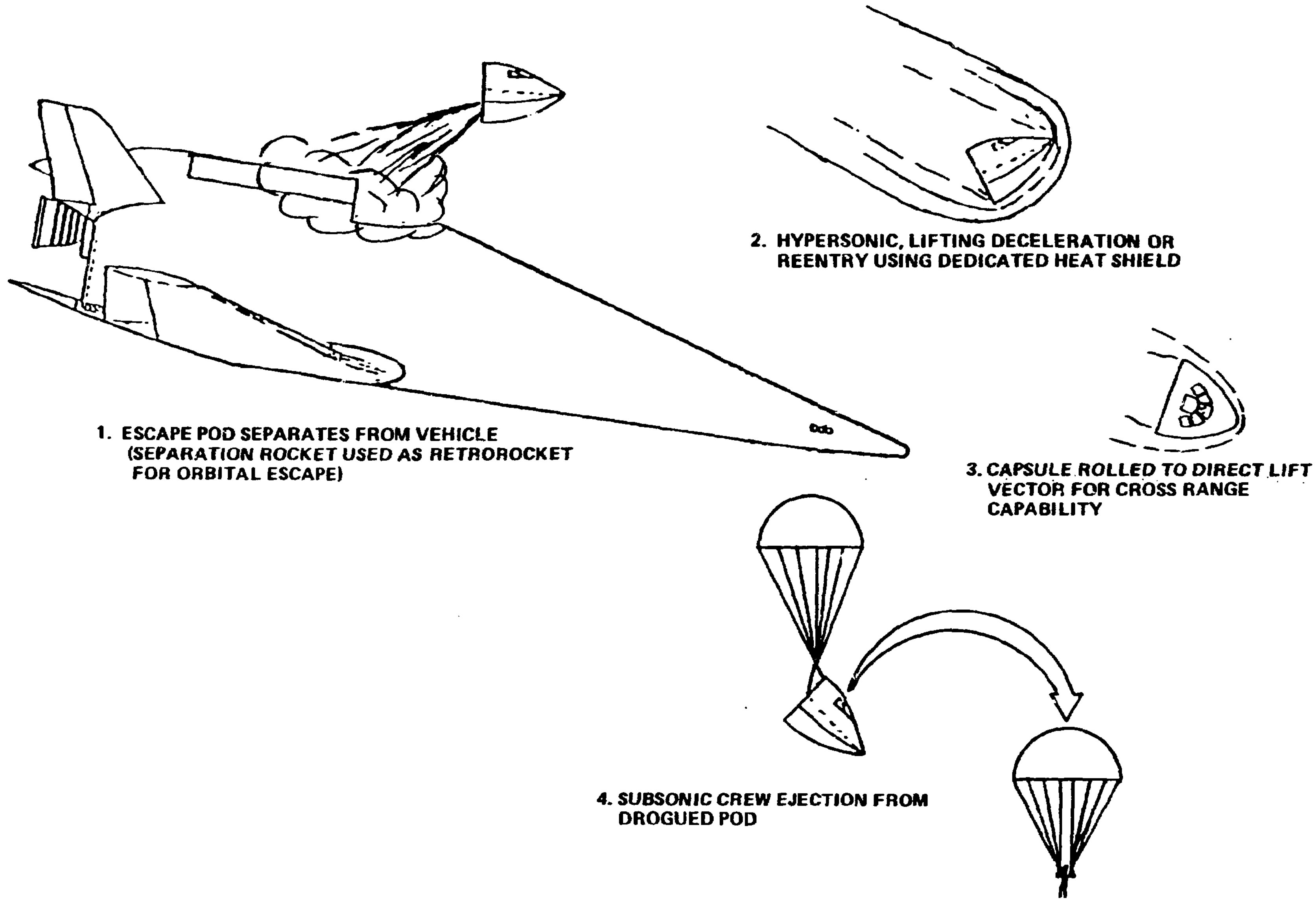


Figure 5.4-4. Recovery Sequence Diagram for Vertically-Launched Vehicle Capsule

6.0 ADVANCED TECHNOLOGIES EVALUATION

Various technologies were investigated for possible application to the HVT crew escape concepts design. These technologies include aerodynamics, thermal protection, propulsion, structures, materials, flight controls, sensors, crew protection, life support, and crew station integration. The objective of this technology evaluation was to answer the following questions:

a. What advances in the applicable technologies have the potential of providing better escape concepts for the HVT vehicles? What good practical options do these technologies provide? For example, the high heat loads during reentry may be designed against by either providing better thermal protection of the structure or by utilizing materials better suited for high temperatures or by a judicious combination of these approaches.

b. What advances in computational tools are available for better predicting the characteristics of the escape vehicles and their environment? For example, simple means of estimating the aerodynamic characteristics of the escape vehicles or the surface temperatures of the escape vehicles during reentry are desired.

c. What potential problems have already been solved, or can be solved with minor modifications, with the latest advances in applicable technologies? For example, can the problem of providing escape system stability and trajectory control be effectively handled by appropriate control laws from the CREST and the ACECT programs (Reference 1, 2)?

d. What results from the studies conducted in the various technologies are directly applicable to the escape concepts being developed?

e. Do the results from the applicable technologies study establish new design requirements or objectives for the escape system design?

The results of the technologies evaluation are discussed in Sections 6.1 to 6.9. The corresponding impact on the detailed escape system definition and subsystem sizing is discussed in Section 7.0.

6.1 AERODYNAMICS

Prediction of an escape vehicle performance requires a good estimate of the escape vehicle aerodynamic characteristics. Various available methods of predicting these aerodynamic characteristics of escape systems were evaluated. These methods included

computational fluid dynamics (CFD) codes, Boeing AEROEZ program, DATCOM methods, PANAIR program, and Aerodynamic Preliminary Analysis System (APAS) analysis code. The salient features of these programs are discussed below.

The CFD methods solve the Navier-Stokes equations for fluid motion. There is much research work going on to make these methods more efficient. However, these are not yet developed enough to simulate 3-D separated flows associated with bluff bodies and high speed. These methods are very complex and costly. A few more years of development are required to make CFD methods a viable option for predicting the aerodynamic characteristics of escape concepts.

AEROEZ is a package of programs developed at Boeing to estimate the aerodynamic characteristics of a vehicle over the entire flow regime from subsonic to free molecular. It is less complex and costly than programs using CFD or panelling methods. It has four modules: DRAGEZ, ACEZ, HYPEREZ and SLIPFREZ (Figure 6.1-1). The DRAGEZ module calculates drag characteristics from subsonic to high supersonic (Mach No. of 4). The ACEZ module calculates lift, aerodynamic center and center of pressure for Mach No. of 8 or less. The HYPEREZ module provides the longitudinal aerodynamic coefficients during hypersonic flow range using Newtonian flow principles. The SLIPFREZ module calculates the aerodynamic coefficients from free molecule flow through slip flow (or viscous interaction) and free molecule flow to hypersonic continuum flow. This evaluation in SLIPFREZ is based upon free molecule flow functions, which are stored for flat plates, spherical segments, cone frustrums, and cylinders. However, AEROEZ is suitable for preliminary design of regular aerodynamic shape bodies only (Figure 6.1-2). It is not suitable for bluff bodies, such as escape capsules or encapsulated seats.

DATCOM is the Air Force compendium of stability and control prediction techniques. It is revised periodically to provide timely data and methods for the design of aircraft, missiles, and space vehicles. DATCOM methods are good for estimating aerodynamic data increments between candidate escape concepts and wind-tunnel-tested escape concepts, provided that the differences in their shapes are small. Thus, these methods are used best only when some wind tunnel data for similar escape concepts already exists. Such data are not available for any escape concept at hypersonic speeds.

The PANAIR program is applicable to general three-dimensional configurations. It uses a high-order panel method, based on the solution of the linearized potential flow boundary-value problem at subsonic and supersonic Mach numbers. Results are generally valid for cases with either subsonic or supersonic flow, but not with transonic flow,

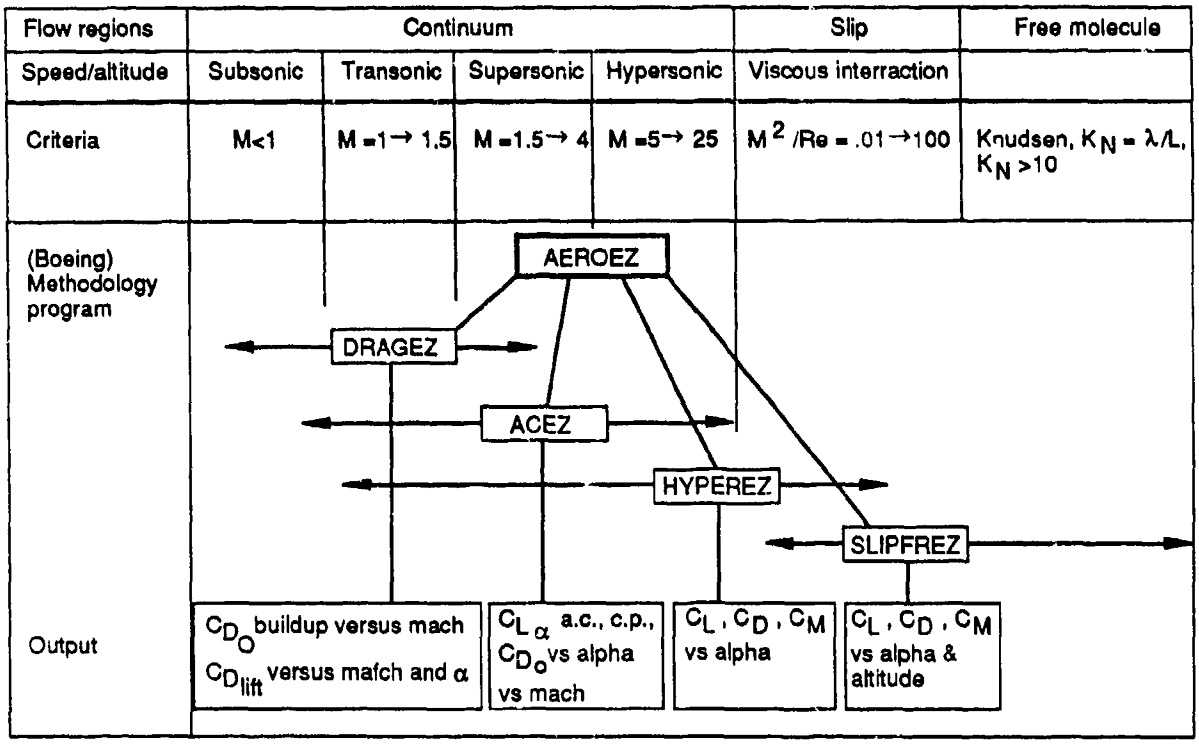


Figure 6.1-1. AEROEZ Aerodynamic Methods Modules

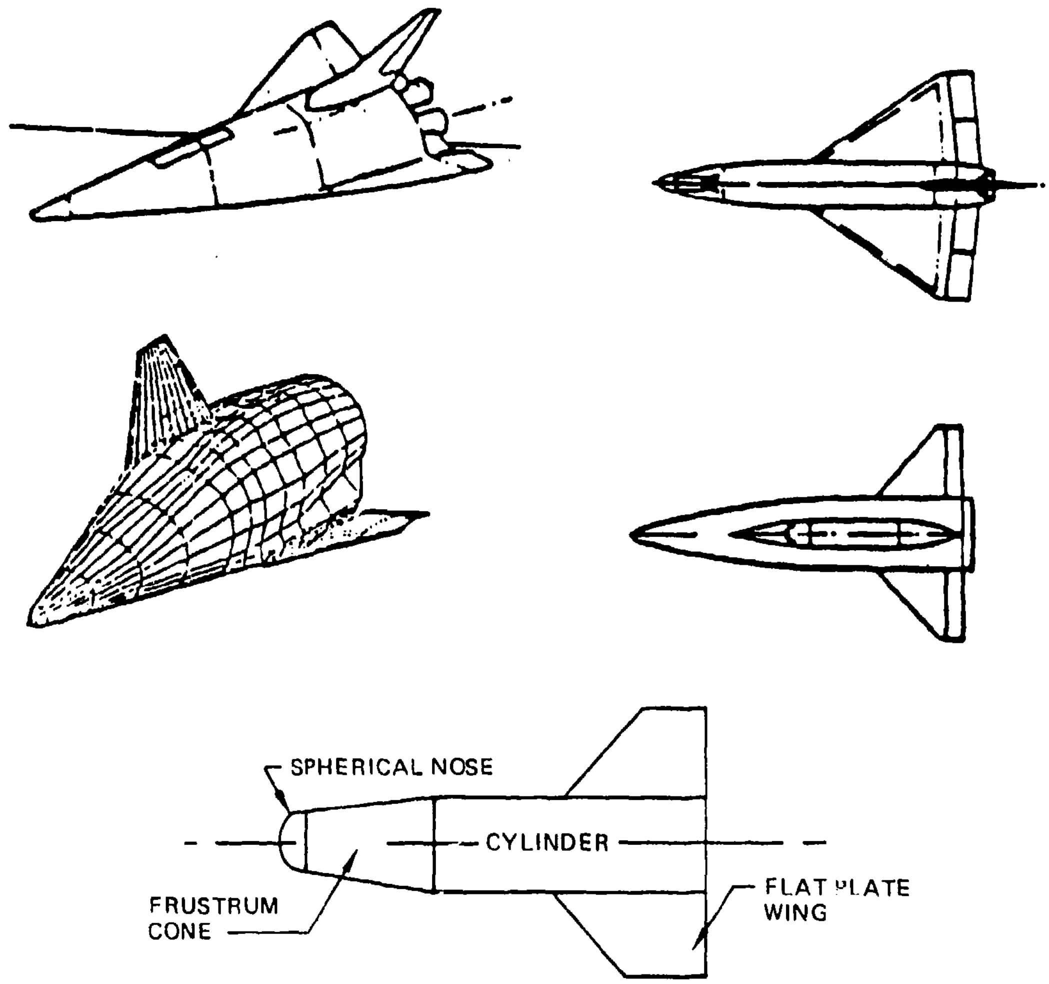


Figure 6.1-2. Re-Entry Body Shapes Suitable for AEROEZ Analysis

within the framework of the linearized potential equation. The results are not usually applicable to cases where viscous effects and separation are dominant. Also, PANAIR is generally not applicable to the hypersonic regime.

The APAS program (References 18, 19) is a good first-order analysis tool for computing aerodynamic forces on blunt bodies with boundary layer separation at supersonic or hypersonic speeds. It was originally developed by Rockwell International for NASA, and has been used and improved at Boeing. It is based on potential theory with edge consideration at subsonic/supersonic speeds and impact type finite element solutions at hypersonic conditions. Three-dimensional configurations having multiple non-planar surfaces of arbitrary planform and bodies of non-circular contour may be analyzed. Static, rotary, and control longitudinal and lateral-directional characteristics may be generated. Usage of this program, supplemented by available wind tunnel data on ejection seats and capsules, appears to be the best choice for estimating aerodynamic coefficients for the HVT escape concepts.

6.2 THERMAL PROTECTION

The HVT crew escape systems must be designed with adequate thermal protection to ensure that the maximum structural temperatures stay below the maximum allowed for the materials and that the heat transmitted to the crewmembers' environment is kept as low as practical.

The magnitude of the temperatures, which the escape vehicle surfaces may reach in the absence of thermal protection can be judged from the data in Figure 6.2-1. These data show that the radiation-equilibrium temperature for a spherical surface with radius of 1 foot can be as high as about 6,800°F, the exact value depending upon the worst combination of Mach no. and altitude. This worst combination will in turn depend upon the maximum dynamic pressure at which escape may take place. The radiative-equilibrium temperature varies inversely proportional to the square root of the radius of the spherical surface. Thus, having a larger-radius surface facing the flowstream helps reduce the maximum surface temperature. However, adequate thermal protection still needs to be provided.

The thermal protection concepts may be active or passive. The active thermal protection concepts proposed for NASP include heat pipes, transpiration cooling, forced convection cooling to fuel, and closed loop convection. The heat pipes, for example, transfer heat from the leading edge aft to a cooler airstream, and thus eliminate the need for a structural material capable of withstanding the 4,000°F to 6,000°F

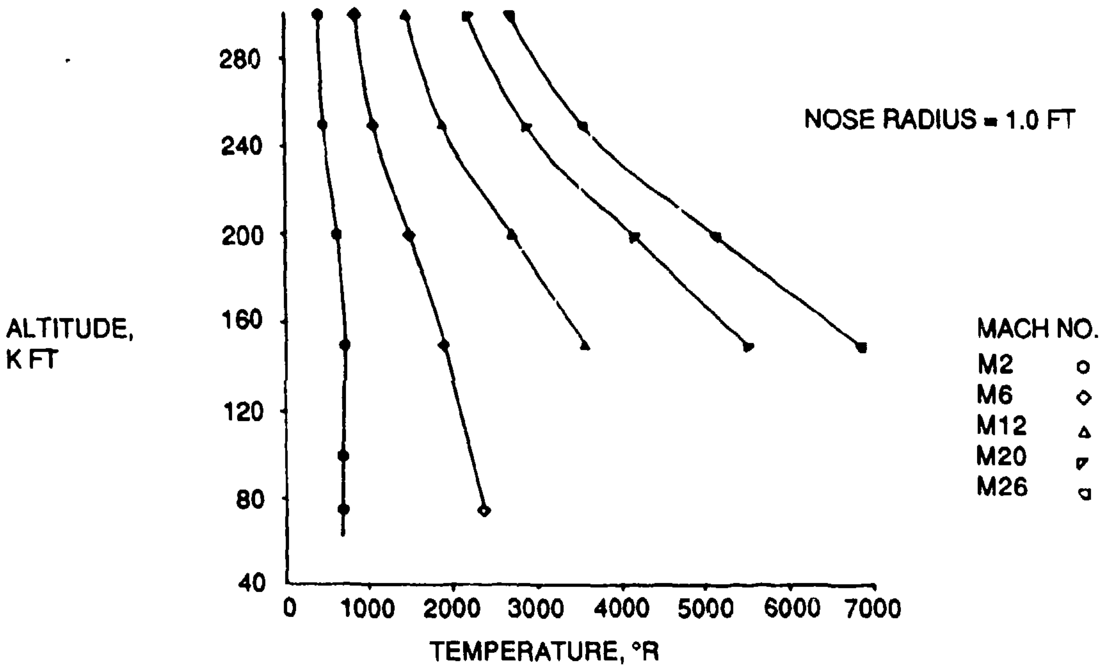


Figure 6.2-1. Radiation-Equilibrium Temperature as a Function of Altitude and Mach Number

temperatures generated by aerodynamic heating. By transferring the heat from the leading edges as shown in Figure 6.2-2, the liquid metal heat pipe limits the maximum temperature the material must withstand to levels within the capabilities of existing alloys (i.e., 2,000°F or less).

The passive thermal protection concepts include heat-shields with ablative materials, high-temperature materials, or both. The heat-shields may be supplemented by insulated structures, water-wall concepts or stored phase change material (PCM).

The active thermal protection systems make sense for the HVT escape systems only if the existing thermal protection systems provided on the main vehicle for normal flight can be utilized. Such was not the case for the four HVT escape system concepts developed under this study. For one-time use on escape systems, heat shields with suitably selected ablative material offer the best choice for the outer structural surface.

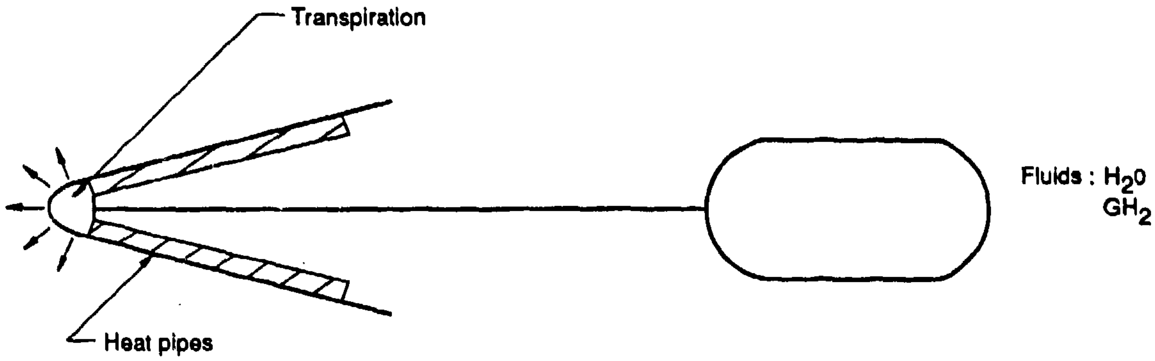
A typical ablative material provides an effective heat sink capacity of severa' thousand BTU/pound of material, compared with less than a thousand BTU/pound for an active thermal protection system.

A thermal protection system must be designed for peak heating rates as well as the total heat load on the escape system during deceleration from high speeds in the atmosphere. The values of the peak heating rate and the total heat load depend upon the trajectory flown by the escape system. For example, during descent from orbital flight, a low L/D vehicle with steeper trajectory loses most of its speed in denser atmosphere, resulting in higher peak heating rate and lower total heat load, compared with a high L/D vehicle flying a shallower trajectory. This is illustrated in Figure 6.2-3, where peak heat flux and total heat pulse are shown for different classes of vehicle.

Various computer programs are available for conducting aero-thermal analysis and evaluating altern ve thermal protection systems. These computer programs are discussed in Section 6.2.1. A discussion of the various ablative materials is provided in Section 6.2.2.

6.2.1 Thermal Analysis Programs

Various thermal analysis programs are available for analysis, which may be required for evaluating the alternative thermal protection concepts. Programs available at Boeing include: C ..vecti eating and Ablation Program (CHAP), Boeing Engineering Thermal Analyser (BETA) and Systems Improved Numerical Differencing Analyser (SINDA). Of these, the CHAP program is ideally suited for the aero-thermal analyses and for selection of ablative materials. It calculates the convective and shock-layer



Active concepts:

Transpiration cooling
- Heat pipes
- Forced convection cooling to fuel
- Closed loop convection

Passive concepts:

- Ablative materials
- High temperature materials
- Insulation

Figure 6.2-2. Some Active Thermal Protection Concepts

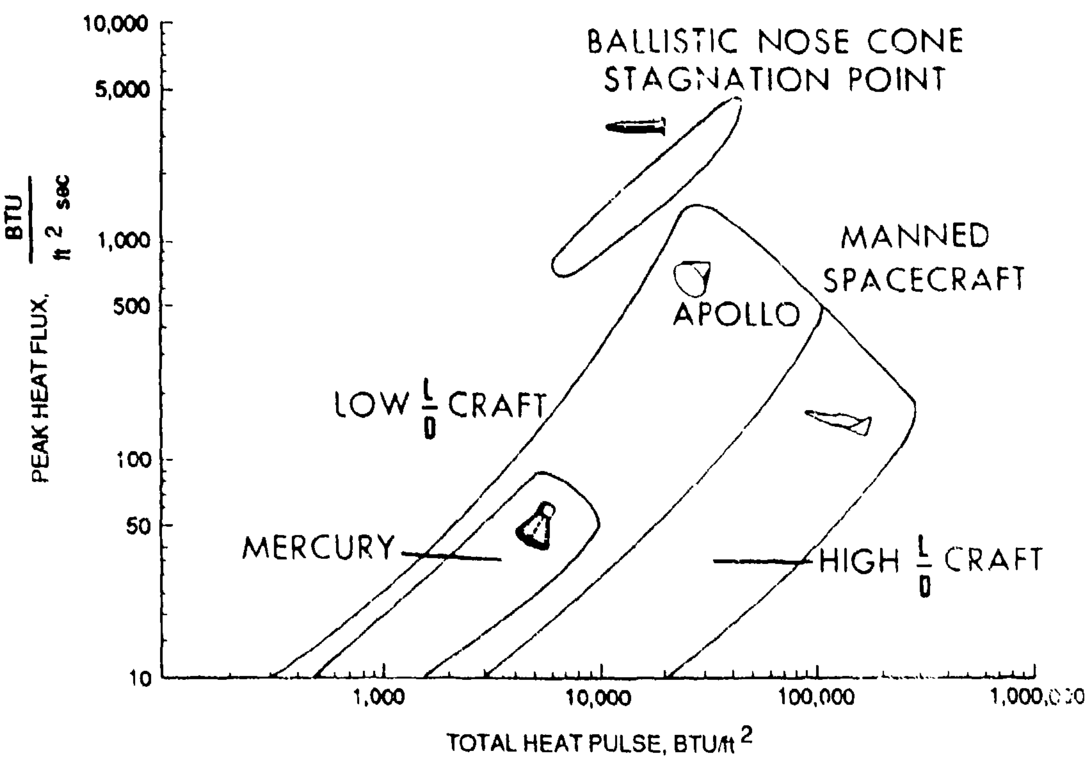


Figure 6.2-3. Peak Heat Flux and Total Heat Pulse for Various Vehicles During Reentry into the Atmosphere

radiation heating rates experienced by a specified geometric shape traversing the atmosphere. Heating rate calculations, based on equilibrium air properties, include the effects of boundary layer transition and geometric discontinuities. It uses the reference enthalpy method for laminar flows, and the Spalding-Chi method for turbulent flows.

CHAP also determines the thermal and structural response of a wall composed of charring or subliming ablation materials, insulation materials, structural materials, or any combination of these, using the calculated heating rates or the predetermined input values. The ablation analysis determines decomposition of the virgin plastic in a plane or indepth, char-layer recession, surface and gas-phase combustion, and nose blunting. The char-layer recession is attributed to combustion, sublimation, and spallation. Char-layer spallation is determined as part of the stress analysis, which includes the combined effects of thermal expansion, aerodynamic shear, configuration flight loads, and the pressures induced by the ablating gases. The ablation analysis and the stress analysis require a total of 48 different material properties, of which 18 are functions of temperature. Properties of commonly used ablators are built into the program.

6.2.2 Ablative Materials

The two major classes of ablative materials, or ablators, are char-forming and non-char-forming. Examples of char-forming materials include carbon phenolic, graphite epoxy, silicone rubber, nylon phenolic, silica phenolic and carbon-carbon.

An ablation process of a char forming ablator is shown in Figure 6.2-4. In this ablation process, the ablative material breaks down and the decomposed material forms a char layer on its surface. The char layer is beneficial since it reduces the heat reaching the decomposing region through its insulative ability, and it re-radiates a substantial amount of heat into the ambient, thus reducing the heat transfer to the primary structure. Gases that are generated during the ablation process diffuse through the char and injected into the boundary layer, thus reducing the external convective heat flux by transpiration cooling. Oxidation reactions between the char surface and the environmental gases can occur, resulting in surface recession. Surface recession also can be caused by aerodynamic shear forces, by pressure from generated gases and by thermal stress. Surface recession is detrimental since it reduces the thickness of the char layer.

For a non-char-forming ablator, the decomposed material absorbs heat through sublimation melting and vaporization. The degradation goal is similar to that shown in Figure 6.2-4 for char-forming ablators. The decomposed material in gas phase is injected into the boundary layer, and the convective heating is reduced by transpiration

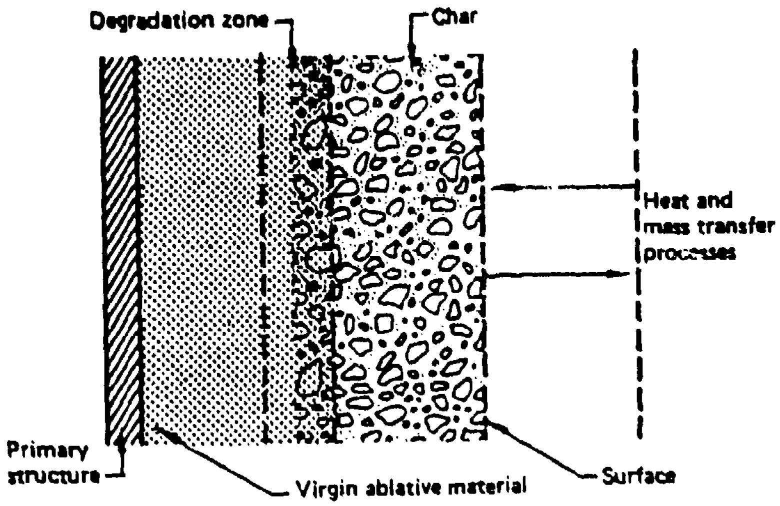


Figure 6.2-4. Diagram of Ablation Process

cooling. The degradation zone is subjected to direct aerodynamic shear stress which will increase the recession rate of the ablation surface. However, non-char-forming ablators are useful at locations where dielectric properties must remain constant, i.e., the ablative material must be transparent over a wide electromagnetic frequency range.

New ablative materials are constantly being developed. However, many of these materials are proprietary. Some of the commonly used ablative materials are described below:

a. Plastic Materials - Plastic materials are widely used ablative materials. They have high heats of ablation. Major limitations are rapid erosion rates during exposure to high gas shear forces, and low strength at elevated temperatures. Thermoplastic resins such as acrylics, teflon and nylon tend to thermally degrade with little or no residue on the ablating surface. Most thermosetting resins such as phenolics and epoxies form a residue of porous carbon following pyrolysis at high temperatures. Plastics reinforced with glass, carbon, asbestos, nylon and other materials are also extensively used.

b. Elastomeric Base Materials - Elastomeric base materials are flexible and easily applied. They are characterized by low thermal conductivity, high thermal protection efficiency at most heat fluxes. Elastomeric materials include both char forming and non-char forming materials. Typical elastomeric ablators are ethylene-acrylic (VAMAC) and silicone rubber. Silicone syntactic foams are used as part of the thermal protective system on the space shuttle external tanks. Elastomeric materials are also widely used on various tactical missiles.

c. Ceramics - Ceramics offer high thermal protection efficiency, but are susceptible to thermal stress failure. Embedding the ceramic in metal honeycomb tends to alleviate this problem. Porous ceramic impregnated with polymers have improved ablative characteristics. Ceramics provide good resistance to shape change.

d. Metal Base Ablators - Metal base ablators are generally porous refractory skeletons containing a lower melting point metallic material. Tungsten matrices with up to 80 percent porosity are used. The porous matrix is infiltrated with metals such as silver or copper. The resultant composite has high strength and good thermal shock resistance. Its low ablative efficiency, high density, and high thermal conductivity tend to restrict its use.

e. Cork - Cork has been used extensively on missiles. The cork used for ablative purposes is a composition of finely ground cork particles and a binder of phenolic resin. It is obtained as sheets of the desired thickness and is usually attached with a room temperature curing adhesive.

f. **Reinforcements and Fillers** - The selection of reinforcements and fillers to add to the base resin can dramatically affect ablator performance. Table 6.2-1 lists some materials used in conjunction with base resins (epoxies, phenolics, silicones, etc.). Reinforcement materials may take the form of woven fabric, tape, fiber mat, tow for filament winding, random bulk fibers and chopped fabric squares. The percentage of reinforcement significantly affects ablator performance; small percentages (3-6 percent by weight) typically only serve to help anchor the char while large percentages (60-70 percent by weight) can govern the overall ablator's performance.

6.3 PROPULSION

HVT escape systems have very stringent performance requirements to provide stabilization and flight control during severance, separation, reentry, and free flight. These performance requirements require use of low-weight propulsion systems with selectable/variable thrust, thrust-vectoring and/or reaction jet capability. The key issues in the propulsion system design are: 1) choice of propellant, 2) best combination of thrust-vector control (TVC) and reaction jet control (RCS) to provide the designed attitude control, 3) actuation for TVC, and 4) power sources for TVC. The current state of the technology in these areas is discussed in the following subsections.

6.3.1 Propellants

The choice of propellant is the biggest driver in the overall propulsion system weight due to differences in providing variable thrust amongst the various propellants. A variable thrust capability is very important for HVT escape systems because of the large time during which attitude control must be maintained with propulsion, before the velocity is reduced from hypersonic speeds to a value permitting drogue deployment. The HVT escape system also requires separation from the vehicle in orbit, deorbit maneuvers and trajectory control during reentry into the atmosphere, which require significantly different thrust profiles than escape at conventional speeds and altitudes.

6.3.1.1 Solid Propellants

Solid propellants are the standard for current escape applications. Solids offer relatively simple and reliable systems with higher safety, and mass fraction than comparable liquid systems. As escape system requirements become more demanding, however, the lack of controllability of solid propellants becomes a serious limitation.

Table 6.2-1. Typical Reinforcements and Fillers

Material	Remarks
Fiber reinforcement	
Asbestos	OSHA regulations discourage use.
Glass (65% SiO_2)	Lower cost, thermal conductivity and melt temperature than high silica.
High silica (95% + SiO_2)	Melts at 3000 F (1649 C).
Quartz (99.95% SiO_2)	Melts at 3000 F (1649 C). Approximately 5 times tensile strength of high silica. No U.S.A source.
Carbon (processed 3092F)	Sublimes at 3650 C (6600 F).
Graphite (processed 3092F)	Higher strength, density and thermal conductivity than carbon.
Low density fillers	
Phenolic microballoons	Pyrolysis with char formation contributes to ablation process.
Glass microspheres	Inert until reaching melt temperature.
Silica microspheres	Inert until reaching melt temperature.
Cork	Natural low density foam. No U.S.A. source.
Low temperature subliming additives	Predominately hydrocarbon chemical structure scorches (caramelizes) at low temperature (350°F) with evolution of large amounts of water vapor and char formation.
Nylon 66	Melts at 260C and decomposes endothermically over 350-500C. When combined with charring base resin, the melting nylon will be retained.
Mo $(CO)_6$ salt	Endothermic decomposition reduces backwall temperature.

While solid propellant exhaust gases can be valved to various nozzles, the inability to throttle solid propulsion systems severely limits their versatility.

Current techniques to improve the versatility of solid systems involves the use of a collection of bit motors coupled to a manifold, control valves, and nozzles. The use of such a system limits the suitable solid propellants to non-metallized formulations producing limited condenses species in the exhaust. Unfortunately, non-metallized propellants are less energetic than metallized formulations. Newer Boron-containing propellants are currently in development and appear promising for use in escape systems. The boron metal improves the performance over that of non-metallized propellants and the thermodynamics of the boron/boron oxide system are such that condensed species do not form until late in the expansion process (down stream of the valves and nozzles). The penalty incurred by the use of boron propellants is an increased exhaust temperature which would require the use of new high temperature materials for valve and manifold construction.

Another possibility for propellant performance improvement is the use of an energetic binder in the propellant formulation. A promising candidate energetic binder is the glycidyl azide polymer (GAP) currently under development by the Air Force Rocket Propulsion Laboratory (AFRPL). The GAP polymer offers more energy than the current standard hydroxy-terminated polybutadiene (HTPB) binder and has been demonstrated to improve the combustion efficiency of boron-containing propellants. Thus a boron containing GAP propellant may offer an improved performance solid propellant for escape systems.

6.3.1.2 Liquid and Gelled Propellants

Liquid propellants offer the ability to throttle the propulsion system; a significant advantage over solids. While liquid rocket control systems have been employed in a variety of manned space systems, they have not been used for escape systems. The toxic nature of the propellants, increased maintenance, and higher system complexity have all accounted for the dearth of liquid rocket escape systems. Despite the problems associated with liquid propellants, the more demanding requirements for hypersonic escape systems require consideration of liquids for this application.

One method proposed to overcome some of the drawbacks of liquid propellants is the use of gelled propellants. Gelled propellants are thixotropic materials that store as gells but behave as liquids when a shear force is applied. Gelled propellants offer the capability of being throttled, higher density than liquids, and are easier to store and

handle than liquids. Also, gelled propellants appear to offer improved safety over liquids with respect to inadvertent mixing of fuel and oxidizer, evaporation of spilled materials, and leakage rates from damaged containers. The most mature gelled propellant combination employs an inhibited red fuming nitric acid (IRFNA) oxidizer gel and a monomethylhydrazine (MMH) fuel gel.

Gelled propellants have not been deployed in any operational system, but are currently being studied for a variety of applications. Three recent reports describing the development of the gelled fuels and oxidizers were provided by Talley Defense Systems, Inc. in 1985 (References 20, 21). Evaluation of mix data for 54 batches of fuel gel and sixty batches of oxidizer gel were provided. The data showed acceptable reproducibility in the density and viscosity (at low shear rates) of both the oxidizer and fuel gells. Characterization of rheological properties at high shear rates has yet to be reported. The resistance to settling of the gells was determined by centrifuging at 500g for 30 minutes (25^{o}C): no sign of settling was observed for the fuel gel while certain batches of the oxidizer gel exhibited some separation. This separation was attributed to moisture contamination of the gelling agent and it is apparent that more work is needed concerning contamination effects on gel properties.

The safety of gelled propellant as compared to liquids was also addressed in the above studies. The results indicated that the gelled propellant offered significantly improved safety and handling characteristics as compared to a comparable liquid system. These data are in conflict with an earlier study of gelled system safety which concluded that, for a particular configuration, gelled propellants increase hazards over a comparable liquid system (Reference 22). The safety of a propulsion system, however, is extremely configuration dependent and a final conclusion on system safety cannot be made until the system configuration is determined.

The above data illustrate that gelled propellants are a promising option for a hypersonic escape capsule propulsion system, but more work will be required to fully characterize gelled propellant properties and safety characteristics.

6.3.2 Thrust Direction Control for Attitude Control

Thrust direction control can be achieved by reaction nozzle control, thrust-vector control, or a combination of the two. The optimum configuration depends on factors such as the number and location of the nozzles, attitude control thrust levels, thrust-vectoring angles, etc. Trapped ball nozzles and jet tabs appear to be leading candidates for thrust vectoring. These can be powered by hydraulic, pneumatic, or

electromechanical actuators. Reaction jets can be controlled by pintle or other hot gas valve arrangements which have been developed for missile guidance and are also being tested for the CREST demonstration ejection seat.

6.3.3 Actuation System Control

Three actuation systems for TVC are available: Hydraulic, pneumatic, and electromechanical. Hydraulic systems generally provide high response, position accuracy, stiffness, and high nozzle torque capability. These systems, however, usually cost more, are heavier, and the presence of hydraulic fluid in the escape vehicle is a negative factor. Pneumatic systems are poorer in frequency response and accuracy, but are usually the lowest cost. Electromechanical systems are practical for low horse power applications, provide accurate response with low weight and cost, but are characterized by low response.

6.3.4 Power Systems for Thrust Direction Control

Hydraulic actuation may be powered by hot gas, stored cold gas, warm gas (2,200°F) generators, or chamber bleed gas. Warm gas can be used with solenoid operated valves in the pulse duration modulation (PDM) mode. Pneumatic systems can use stored pressurized gas or hot gas generators to directly drive an actuator, or indirectly through gas turbines with speed reducers. The horsepower-to-weight ratio is higher for pneumatic power compared to electromechanical. The main disadvantages of the pneumatic system are low static stiffness, a tendency toward instability, and a slower response time due to gas compressability and low viscosity. However, the addition of extra pressure chambers and electronic compensation in the loop closure may be sufficient.

6.4 MATERIALS

The selection of materials for HVT escape systems needs to be made together with the selections of thermal protection method and structural concept. Use of active thermal protection techniques will typically make use of material with very high temperature capability more attractive than when ablative materials are used for the high heating rate surfaces. The various potential material candidates for HVT escape systems are discussed below in three different categories.

The first category consists of materials used for reuseable surfaces of the escape system which also form the exterior surface of the vehicle. Three metallic materials

offering the potential of greatly improved structural efficiency at high temperatures are: 1) rapid solidification technology alloys (RST) particularly improved titanium alloys, 2) metal matrix composite (MMC) materials, utilizing the extremely high strength of fiber materials embedded in high temperature metallic matrix materials, and 3) advanced refractory metals such as columbium alloys capable of withstanding high temperatures without the oxidation problems associated with current refractory alloys. In addition, the further development of ceramic materials such as advanced carbon/carbon (ACC), and ceramic/ceramic composites, offer the opportunity to design reentry-sensitive components such as nose cones and leading edges with greatly improved strength to weight ratios. The specific strengths of some of these materials are shown as a function of temperature in Figure 6.4-1.

The second category consist of materials that would only be exposed during escape system activation. These materials will only be used once. Metal matrix and titanium honeycomb sandwich construction may be used as well as high temperature thermoplastic and thermosetting carbon fiber advanced composites, which are protected with insulation tiles or blankets, heat shields, or ablative coatings.

The third category includes materials for interior components which could include (depending on the concepts) side panels, floor panels, crew seats and equipment covers. Thermal requirements will be significantly less for these components. The main emphasis for these components is on light weight, reliability and low cost. Thermoplastic and thermosetting, graphite-reinforced, advanced composites should be considered for interior applications. Fiberglass or nomex honeycomb core materials are considered where possible to reduce weight. Light-weight, aluminum-lithium alloys would also be considered as candidates.

6.5 STRUCTURES

The basic structural technology developments required to support a hypervelocity vehicle design are directly applicable to the development of crew escape system concepts.

The selection of the structural concept for an escape vehicle goes hand-in-hand with the selection of the thermal protection method and the structural material. Various advances in structural design are being developed for the HVT vehicles to minimize structural weight. Among the more promising developments are high temperature brazed honeycomb panels, lightweight structural frame technology, and vacuum jacket tank structural concepts. These concepts are discussed in the following subsections.

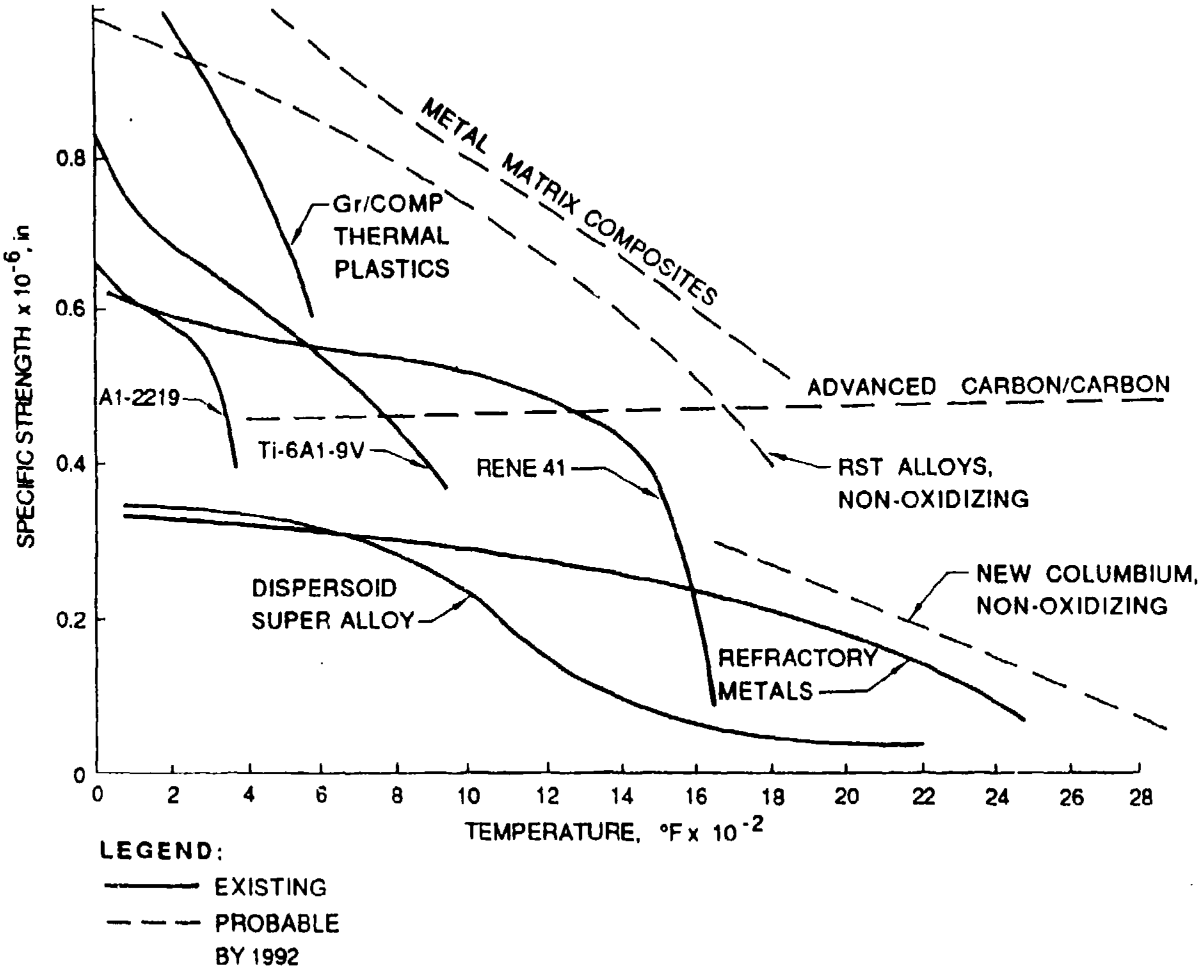


Figure 6.4-1. High Temperature Materials

6.5.1 Continuous Brazed Honeycomb Panel

Continuous brazed honeycomb panel fabrication process improves panel braze integrity and reduces intergranular attack on core material by braze alloys. The incorporation of this honeycomb panel construction, in those areas of the escape capsule exposed to thermal levels compatible with the panel materials (up to approximimently 1500°F), may result in significant weight reductions and decreased fabrication costs as well as increased panel reliability through panel quality level improvements.

This process has been demonstrated in small scale developmental systems and equipment is in place to begin fabrication of larger panels. Current hardware demonstrations have utilized existing high temperature alloys, and there does not appear to be any restriction to its applicability to planned high temperature improved-metal matrix composite materials planned for use on future hypersonic vehicles. In addition to its basic application as a high strength, high stiffness structural panel material, it could be considered for use in such items as post-separation aerodynamic control or stabilization surfaces, and may be considered as a candidate material for the outer shell of a separable crew escape enclosure.

6.5.2 Lightweight Frame Construction

Lightweight frame construction design (Figure 6.5-1) provides increased frame stability at significantly reduced frame weights. The incorporation of this frame design will permit considerable reductions in crew compartment structural weights. The basic processes required to fabricate the lightweight frame design have been demonstrated on small scale development hardware, utilizing existing materials.

6.5.3 Vacuum Jacket Tank Structural Concept

Vacuum jacket tank structure concept provides the most efficient thermal isolation system to be studied to date. This system allows the minimum number of thermal conduction paths between the inner and outer shells, while still allowing the inner and outer structural element of both to contribute to the vehicle bending strength. While this system is heavier than some of the other structural concepts under consideration for hypersonic vehicles, its extremely efficient thermal isolation characteristics may prove desirable in the crew compartment area where exterior skin temperatures are significantly higher than those encountered at locations farther aft on the vehicle.

A finite element model analysis of this structural system has been completed for a typical hypersonic vehicle configuration. The weight penalty for this system, as applied

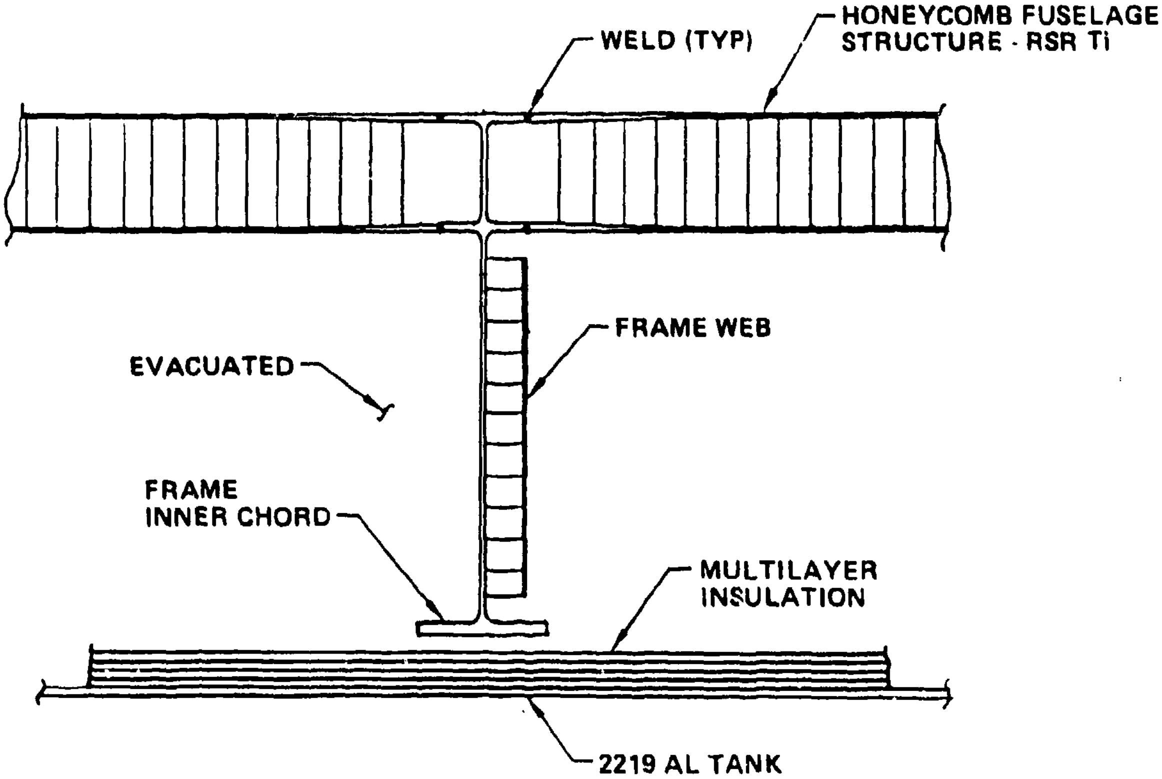


Figure 6.5-1. Structural Design Concepts

to the entire fuselage structure, is unacceptable, however; for a relatively small area such as the crew compartment, the increased insulation efficiency necessary to compensate for higher thermal profiles may make the vacuum jacket concept a viable alternative.

6.6 FLIGHT CONTROLS

A good control law for an HVT escape system is required for:

- o Trajectory control of the escape system, including steering away from the vehicle.
- o Keeping the escape system stable in all three aces.
- o Avoiding skipping motion of the escape system during reentry.
- o Selecting the timing for the deorbit maneuver, if done automatically instead of manually.
- o Life threat assessment.
- o Pointing the heat shield forward during reentry or at hypersonic speeds, as applicable.
- o Sequencing events such as parachute deployment.

Thus, the control law for an HVT escape system has to perform many more functions than those performed for an ejection seat or a conventional escape capsule. The control laws designed for the CREST demonstration ejection seat (Reference 2) and for the various capsule configurations under the ACECT contract (Reference 1) are applicable for low altitude and low speed escape conditions on the HVT vehicle. However, control low work is required to extend it to perform the additional control functions for an HVT escape system.

Advanced techniques for multivariable control laws and adaptive control laws synthesis are available for application to the HVT escape system control law development. For example, the MPAC computer program developed at Boeing can be used to synthesize the optimal control laws. It synthesizes full-order controllers, which are then reduced in size by modal residualization, as well as the reduced-order controllers directly. The MPAC design environment also allows calculation of frequency response, root loci, covariance analyses and time responses. The control laws designed by MPAC can be easily transferred to EASY5 and EASIEST programs (Reference 23) for nonlinear simulation without requiring manual transfer of various data.

6.7 SENSORS

The desired control of the HVT escape systems will require sensors for measurement of the following parameters:

a. Linear accelerations in all three axes
b. Angular rates in all three axes
c. Escape system attitude: pitch and roll
d. Sink rate
e. Altitude above ground
f. Pressure altitude
g. Dynamic pressure
h. Escape system angle of attack and sideslip angle
i. Propellant temperature
j. Position w.r.t. known points on earth

A detailed trade study of sensors "a" through "i" above was conducted for application to the CREST demonstration ejection seat, which showed that its requirements can be best satisfied by a combination of continuously-operating Inertial Sensor Unit (ISU), a pitot-static tube and an airplane-mounted radar altimeter (Reference 24). A similar conclusion was reached under the ACECT program for capsule application. However, future developments in technology may affect the optimum sensor choices. Some of the sensor selection consideration are discussed below.

The ring laser gyros (RLG) have high reliability, but the high accuracy requirement results in a large, heavy instrument. The Air Force and Navy programs on high accuracy RLG development may result in improvements in this situation. Fiber optics gyros promise high reliability and low weight. However, current performance capability is only about one degree/hour. Mechanical gyros, including single degree-of-freedom and two degree-of-freedom wheel gyros, and electrostatically suspended gyros (ESG) are also good candidates.

It would seem to be a foregone conclusion that Ground Positioning System (GPS) should be incorporated into an HVT vehicle navigation system suite. The crew escape system will use this information to establish position w.r.t. known points on earth at escape initiation. During some flight regimes, plasma sheath effects may preclude satisfactory reception of the GPS signals unless special measures are taken. Some potential measures include shadowing the antenna, actively producing a window using a magnetic field, and actively and adaptively interacting with the plasma itself (plasma

modulation). One of the critical elements in integrating GPS into the navigation system is the antenna. For missions which do not spend much time in plasma sheath conditions, it may be acceptable to forego GPS updates during plasma blackout, relying on the Inertial Navigation System (INS) to keep the navigation error within bounds.

Successful use of GPS for satellite navigation has been demonstrated using the Landsat-5 satellite. Signal tracking in an orbital dynamic environment does not seem to be an issue. However, the expected relatively long periods of acceleration and deceleration of the HVV may result in a requirement to modify the tracking loops to avoid excessive hangoff in the presence of the sustained acceleration.

One ongoing in-orbit navigation program is the Air Force MADAN (Multimission Altitude Determination and Autonomous Navigation) program. The MADAN system consists of three strap-down star sensors and an Earth horizon sensor. Navigation determination is the same as that used in celestial navigation on the earth. The navigation accuracy goal is 900 meters, being limited principally by variation in the earth's infrared horizon. Attitude determination accuracy is about 6 arc seconds. Other promising methods include SHAR (Stellar Horizon Atmospheric Refraction) and SHAD (Stellar Horizon Atmospheric Dispersion). The first method measures the refraction angle of a star as it approaches the earth limb, while the second method measures the dispersion between two colors under the same conditions. The SHAR and SHAD techniques have the advantage that an earth horizon sensor is not required. Potential accuracy is less than 100 meters, given sufficient star occultation sightings.

Another orbit navigation program is the AF Space Sextant program with Martin Marietta. This is a highly accurate, but somewhat heavy stellar sextant/INS system.

6.8 CREW STATION

The developments in crew station technology which may have a significant impact upon design of the HVT escape concepts may be subdivided into the following two categories:

- Crew station design methodology
- Crew station hardware and software

The recent developments in these two areas are discussed in the following subsections.

6.8.1 Crew Station Design Methodology

Significant advances in the crew station design methodology have been or are being made under the Cockpit Automation Technology (CAT) program (Reference 25) and NASA Standards for Man/System Integration (Reference 26).

The CAT program will provide a comprehensive data base and set of design methodologies for the solution to specific cockpit crew integration problems. Anthropometry computer models such as COMBIMAN, hierachial functional flow diagraming computer programs, automated task timelining, automated functional allocation, as well as powerful 'what if' computer models will be integrated into a single comprehensive package. The unified system will include all air vehicle subsystems, e.g., avionics, propulsion, flight control, life support, escape, etc., insofar as they impinge on the cockpit design. Man-in-the-loop full mission simulation to test the practicality and goodness of the system concepts will be much more efficient and less costly. Multidisciplinary skills will be brought to bear on the problem with unparalleled efficiency. It will provide friendly, relatively simple, elegant user interfaces. The fidelity and confidence in decisions regarding the design will be much higher with less cost. Also this fidelity can be obtained much nearer the beginning of the program. Human performance data for human engineering trades could be handled much more easily and with less use of empirical methods or qualitatively. A more quantifiable approach would be practical. This set of technologies may be available in the early 1990's.

NASA-STD-3000, MSIS (Man/System Integration Standards) is a Boeing-developed document, which contains the latest human limitation criteria and design requirements. The document is similar in intent to MIL-STD-1472. Existing standards have been reviewed, source data have been collected and the standards have been organized and published with the support of a government/industry advisory group. Data have been collected and standards developed in the areas of mobility, vision, comfort, ingress, egress, acceleration effects and personnel protection.

6.8.2 Crew Station Hardware and Software

Significant developments are taking place in the areas of virtual instrument technology, helmet-mounted display technology, voice interface technology and tactile data input technology, and artificial intelligence.

The virtual instrument technology saves weight and reduces sensory overload by selective filtering of data to be displayed, the instruments exist electronically on a CRT

or flat panel display screen and can be commanded to rearrange themselves as necessary for the various parts of the mission.

The helmet-mounted display technology allows use of high resolution cathode ray tubes or some type of image device to present filtered data to the pilot from inside the helmet. This has an enormous weight saving potential by eliminating a significant portion of the cockpit instrumentation.

The voice interface technology allows the pilot to simply talk to the flight director system and avionics system and the craft can respond to his commands or inquiries. This reduces workload and improves user interface. This also can save a significant amount of weight by eliminating some cockpit instrumentation and reducing the need for visual monitoring of certain data. The implementation of this technology may require a small addition of weight for the computer.

The tactile and other modalities of data input/output technology between crewmembers and vehicle are also under development. Innovation exists today for precise detection of exact location of pilot's eye or pointing fingers. This information can be used in conjunction with image devices to produce a virtual image of the cockpit and the surrounding space. This can be a simplified format (like cartoon) to reduce sensory overload. When the crewmember points or looks at a virtual switch in his field of view, the set of three orthogonal radio-frequency coils detect the pilot's initiation of the virtual switch and the software gives commands to the piezoelectric tactile feedback devices in his gloves which provide the pilot a positive feedback. This technology also can reduce weight in the cockpit by eliminating the physical switches, actuators, etc.

Artificial Intelligence which includes expert systems could be used as means to reduce weight in the escape pod/cockpit. This technology has enormous potential with regard to workload reduction and as decision-aids to crewmembers in extremely complex or exotic environments.

6.9 LIFE SUPPORT

Current and projected future advances in life support technologies can be expected to have a significant effect on the feasibility of the HVV escape system concepts. Factors that must be considered in selecting and designing a life support system include, but are not limited to, mission effectiveness, quick response capability, crew comfort and acceptance, safety, and weight.

Two of the major developments in life support area are the Tactical Life Support System (TLSS) and improvements in pressure suits. These are discussed in the following subsections.

6.9.1 Tactical Life Support System (TLSS)

TLSS (Reference 28) was designed to provide personal protection from the potentially hazardous aerospace environment. Specifically intended for application in tactical aircraft, this system of personal protection includes positive acceleration protection to sustained $+9G_z$, altitude exposure to 60,000 feet, cockpit thermal conditions up to 50°C, head protection from incidental impact during buffet and emergency escape, ocular protection from known laser hazards and nuclear flash, all while being compatible with or inherently providing both chemical warfare defense and restraint in the cockpit. While not specifically designed for use in the HVV, the TLSS concepts could be readily adapted for use in these advanced vehicles. The HVV configuration, applicable for moderate-to-low ambient cabin pressures, would center around the TLSS partial pressure suit concept to provide "get-me-down" and ejection capability from 60,000 feet The TLSS personal ensemble, helmet and helmet mounted systems (Figure 6.9-1) and integrated garment would sustain the positive pressure breathing (PPB) with chest, abdominal, and leg counterpressure required for altitude protection. Pressurization of the aircrew's personal equipment to these schedules would maintain the oxygen partial pressure in the lungs at the levels specified in Figure 3.2-3 and prevent blood pooling in the abdomen and lower extremities.

TLSS can also provide acceleration protection during crew escape (i.e., ejection) and high acceleration vehicle maneuvers. Separate pressure schedules are followed in inflating the lower garment (not unlike the current CSU-13/P G-suit) and the mask and jerkin as a function of G. Lower garment inflation would be supplied from either a separate anti-G value (if one is required) or from a device integral to the breathing regulator (both concepts were developed under the TLSS contract).

Features which must be added to the current TLSS to provide altitude capability above 60,000 feet include:

a. Full face seal with separate oronasal cavity
b. Full neck bladder
c. Pressurizable earcups
d. Arm bladders

6.9.2 Pressure Suits

Current pressure suits, like those used in the SR-71 and U-2 (i.e., GN-S1010B, GN-S1030, GN-S1031) and for general Air Force applications (i.e., AP22S-6), provide aircrew protection and survival for missions to altitudes in excess of 60,000 feet and/or

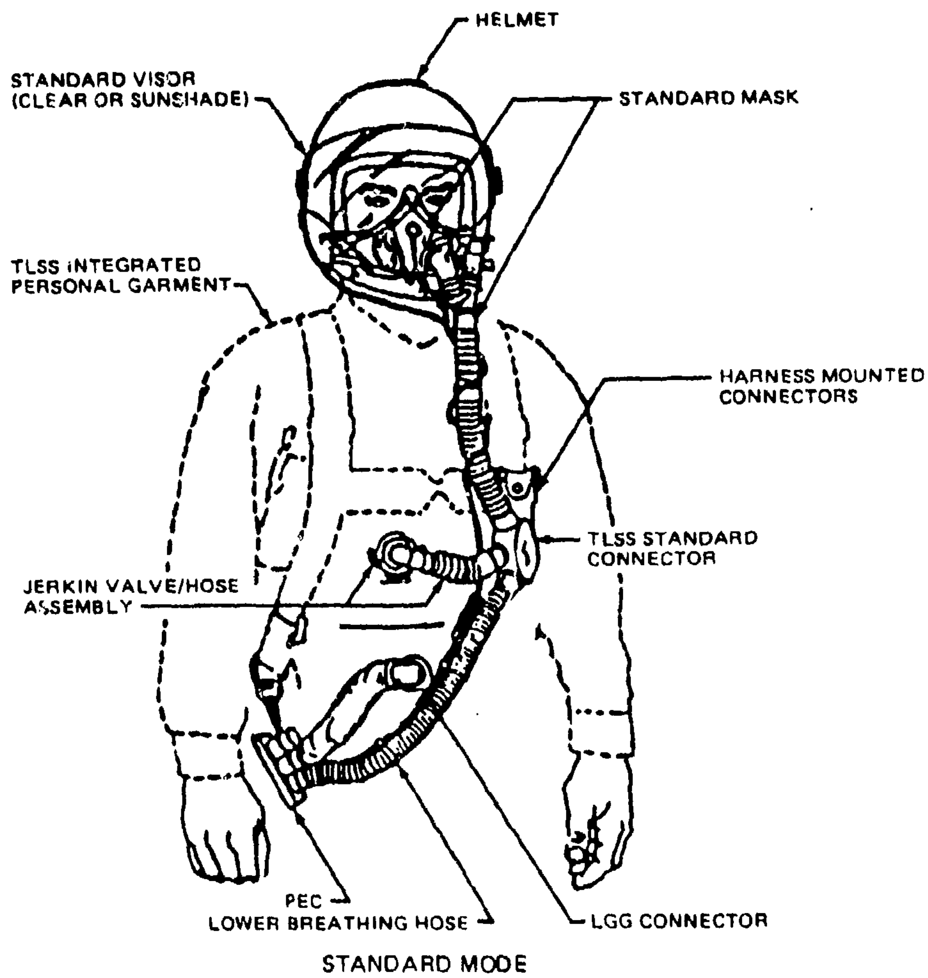


Figure 6.9-1. TLSS Equipment

for extended operations, following the loss of cabin pressure, at altitudes above 50,000 feet (Reference 29). Consistent with the requirements presented in Figure 3.2-3, these suits are generally designed to provide a 100 percent oxygen environment at 3.5 psia for aircrew survival in an unpressurized cockpit or following a decompression. While providing an increased factor of safety for aircrew survival during high altitude/space operations, a number of drawbacks (e.g., reduced visibility, mobility, dexterity, comfort) have resulted in only marginal aircrew acceptance. In addition, the added requirement for prebreathing 100 percent oxygen for 60 to 90 minutes prior to high altitude exposure (for blood denitrogenation to prevent the bends) essentially prevents an HVV rapid response if such a mission is being considered.

Two areas of potential improvement in pressure suit concepts are the zero prebreathe suit and the quick-don suit. The zero prebreathe pressure suit has been designed to operate at pressures of 8 psia to eliminate the 60 to 90 minute prebreathe requirement. This, however, has produced unique problems in suit development, particularly in the area of glove and joint development where the increased pressure makes motion of extremities difficult. Current preliminary designs have therefore begun looking at mechanical means to enhance motion as well as special "soft joints". The quick-don suit, an idea which hopefully could be integrated with the zero prebreathe suit, is an attempt by engineers to reduce suit donning time from 30 minutes, for current suits, to 10 minutes. Current concepts include both the two-piece suit, which parts along a diagonal plane through the torso, and a "refrigerator door" concept, in which the crewmember climbs through a door in the back and then closes the door.

Note that although the development of these suits will eliminate oxygen prebreathing requirements and reduce donning time, the problems associated with current suits' complexity, weight, and bulkiness will not necessarily be solved.

7.0 DETAILED ESCAPE SYSTEM DEFINITION AND SUBSYSTEM SIZING

This section discusses the details of the HVT escape system design, sizing and characteristics which were necessary to establish, so that a meaningful trade study between the alternative concepts can be conducted.

7.1 AERODYNAMIC COEFFICIENTS

A good estimate of aerodynamic coefficients, such as those for drag, lift and pitching moment, is necessary to evaluate performance of the HVT escape concepts during various escape conditions. As discussed in Section 6.1, the APAS program was the most efficient analysis tool available for estimating the aerodynamic coefficients and was therefore, used in this study.

Figure 7.1-1 shows a typical APAS panelled model of the HLV pod capsule. Such APAS models were used to determine the aerodynamic characteristics above Mach 3. These data were then extended to lower speeds by assuming variations with speed to be similar to those determined by wind tunnel tests on CREST ejection seat and a conventional pod capsule.

An altitude of 100,000 feet was used for all APAS simulations. The aerodynamic data variations with altitude were found to be negligible.

The calculated aerodynamic data are shown in Figures 7.1-2 through 7.1-16 with the correspondence to escape concepts as follows:

Figure Number	Escape Concept
7.1-2 to 7.1-4	Dual-place encapsulated seat
7.1-5 to 7.1-7	Single-place encapsulated seat
7.1-8 to 7.1-10	HLV pod capsule with wings deployed
7.1-11 to 7.1-13	HLV pod capsule with wings not deployed
7.1-14 to 7.1-16	VLV pod capsule

The pitching moment coefficient for each concept was calculated at the estimated center-of-gravity (c.g.) for each concept. The c.g. locations and the orientation of the x-axis, from which angle of attack was calculated, are shown in Figure 7.1-17.

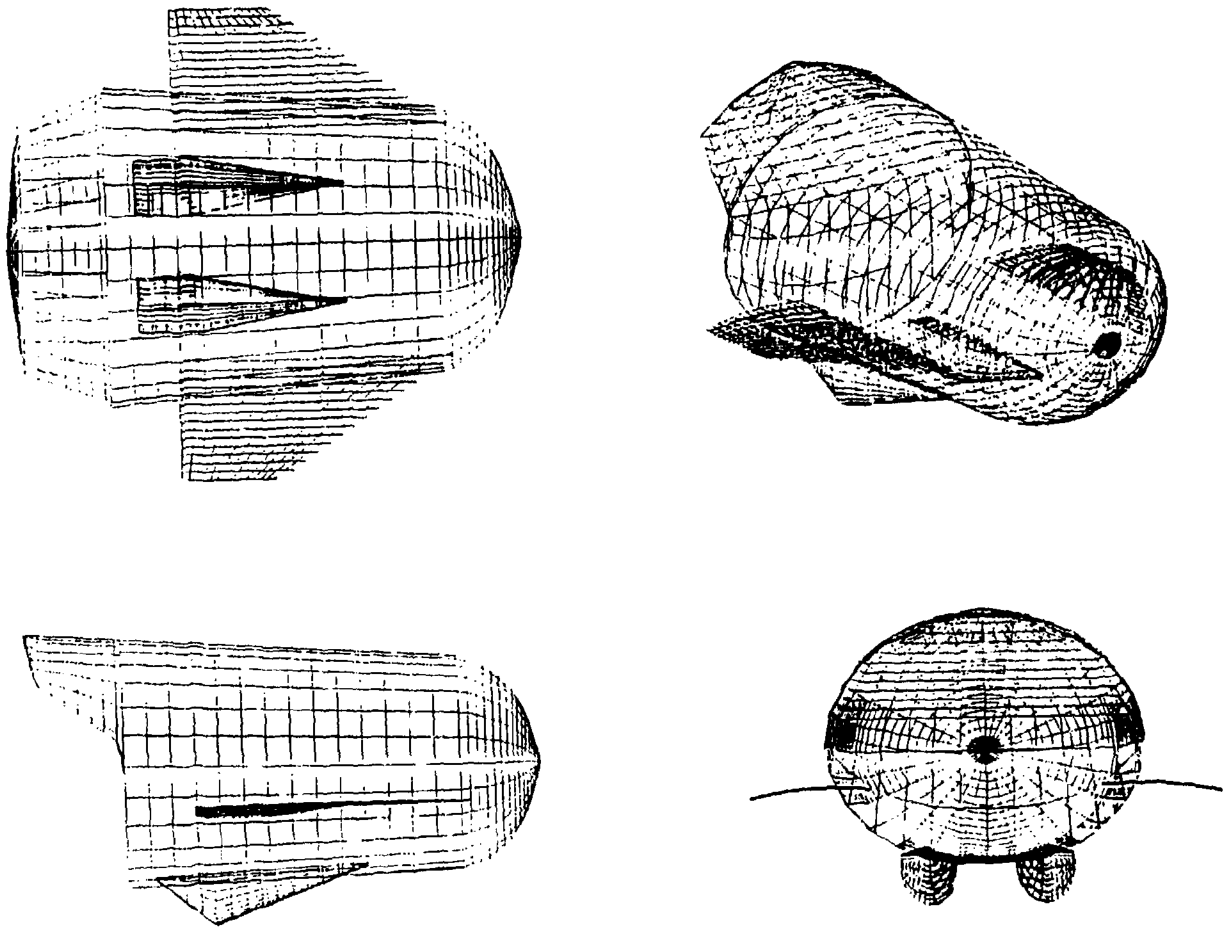


Figure 7.1-1. Typical APAS Panelled Model of the HLV Pod Capsule

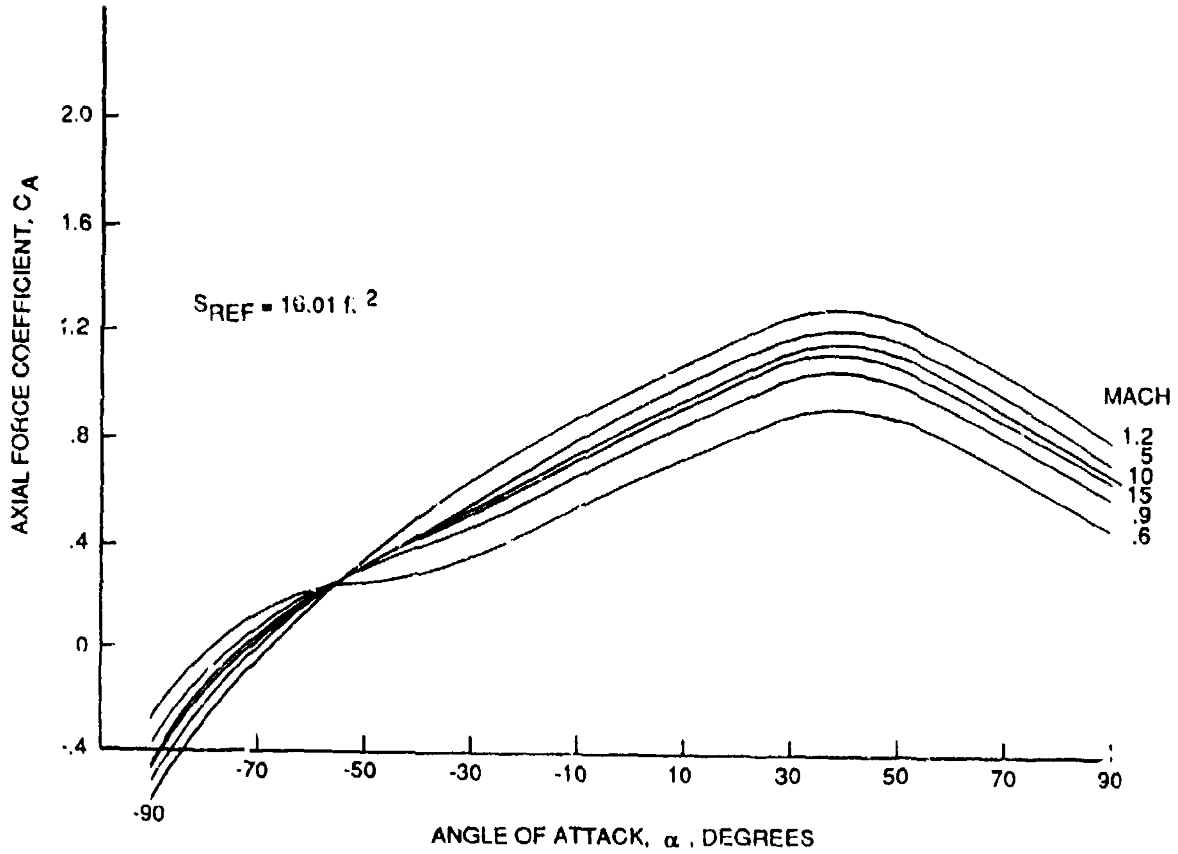


Figure 7.1-2. Axial Force Coefficient for Dual-Place Encapsulated Seat

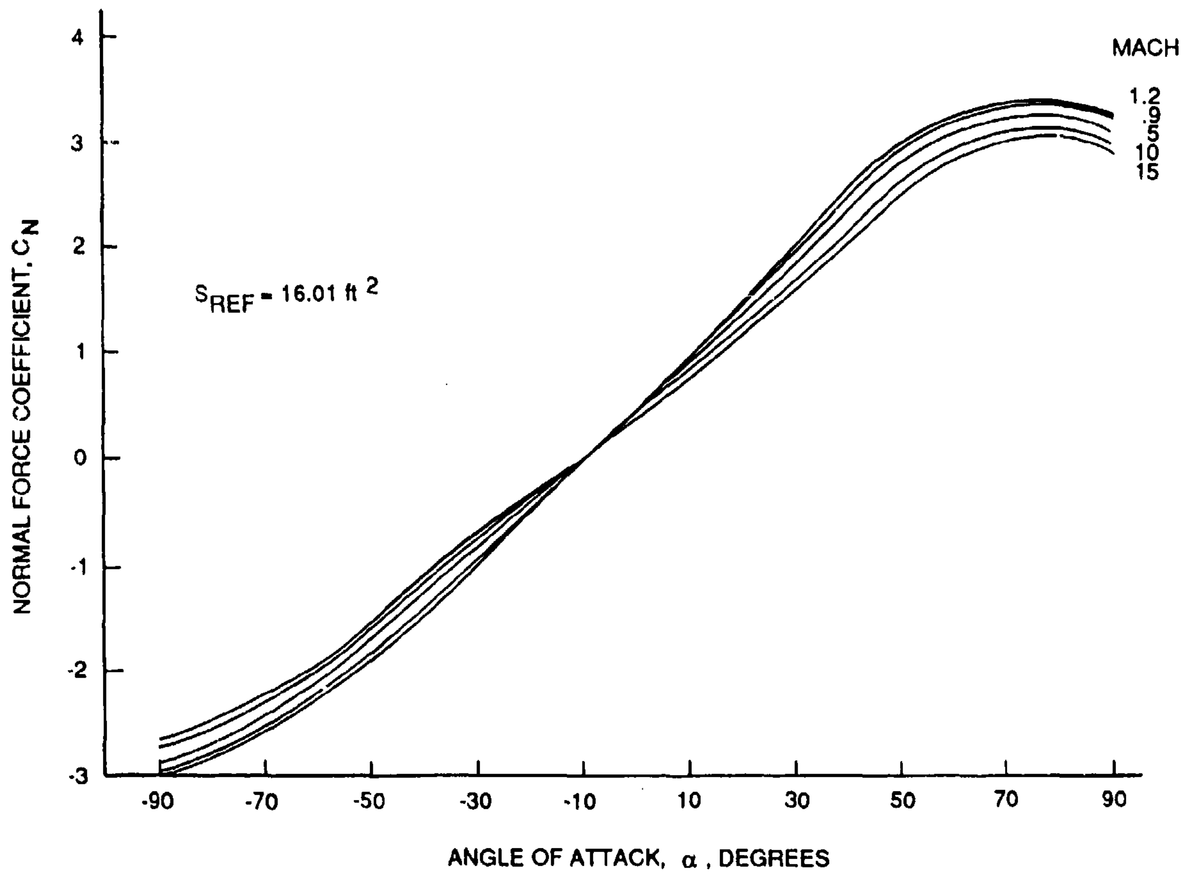


Figure 7.1-3. Normal Force Coefficient for Dual-Place Encapsulated Seat

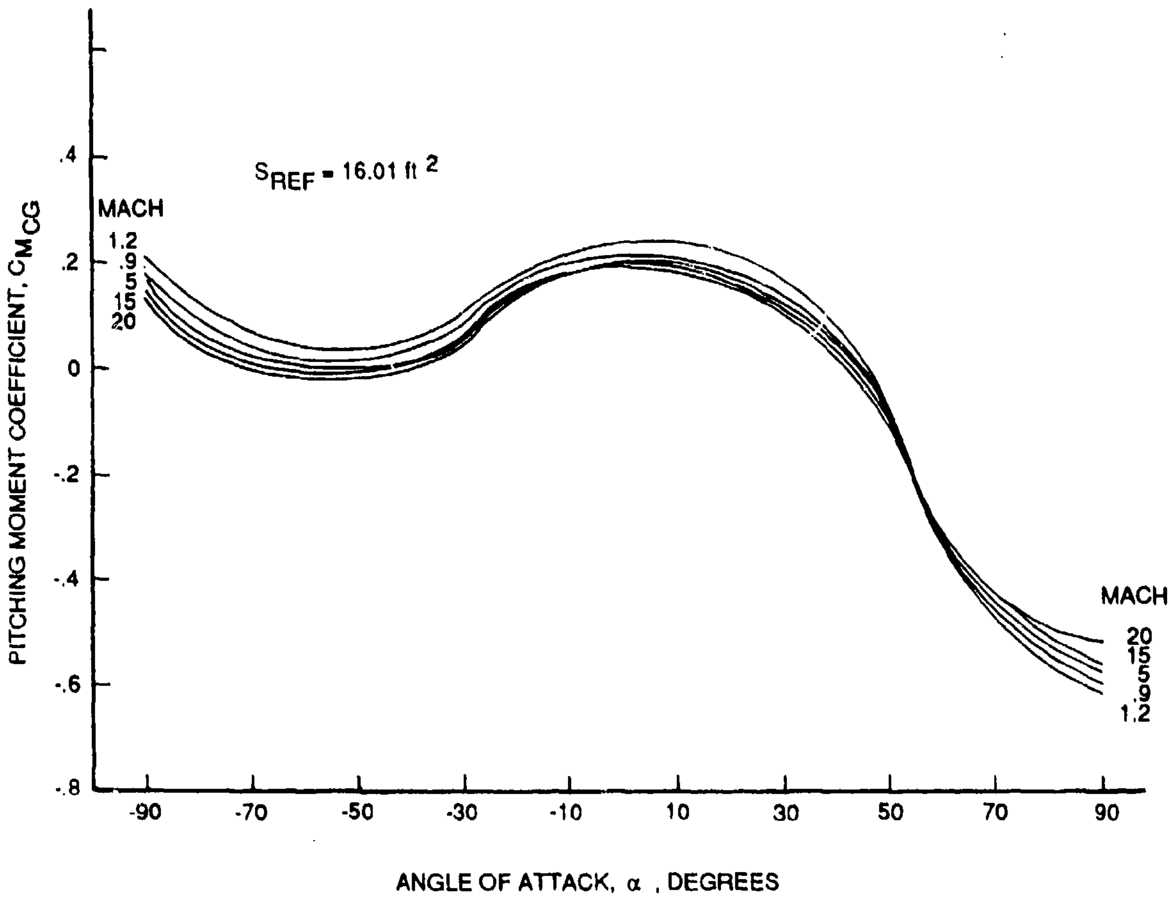


Figure 7.1-4. Pitching Moment Coefficient for Dual-Place Encapsulated Seat

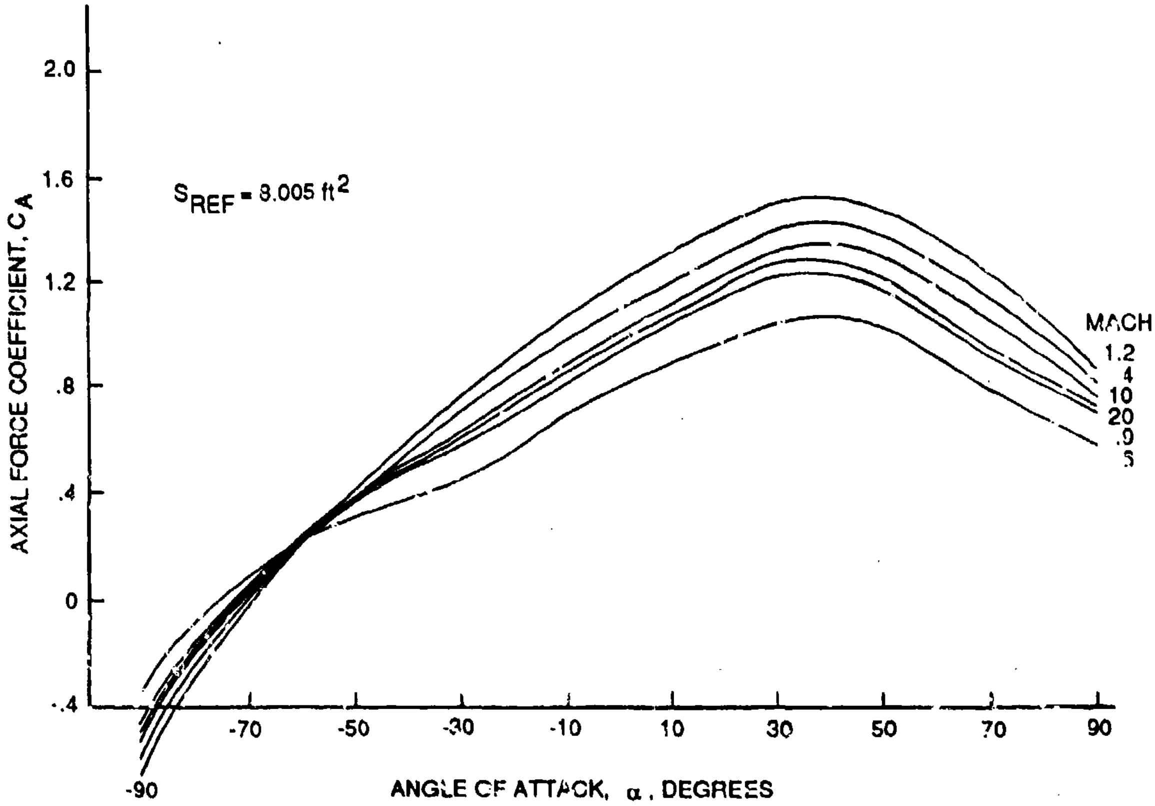


Figure 7.1-5. Axial Force Coefficient for Single-Place Encapsulated Seat

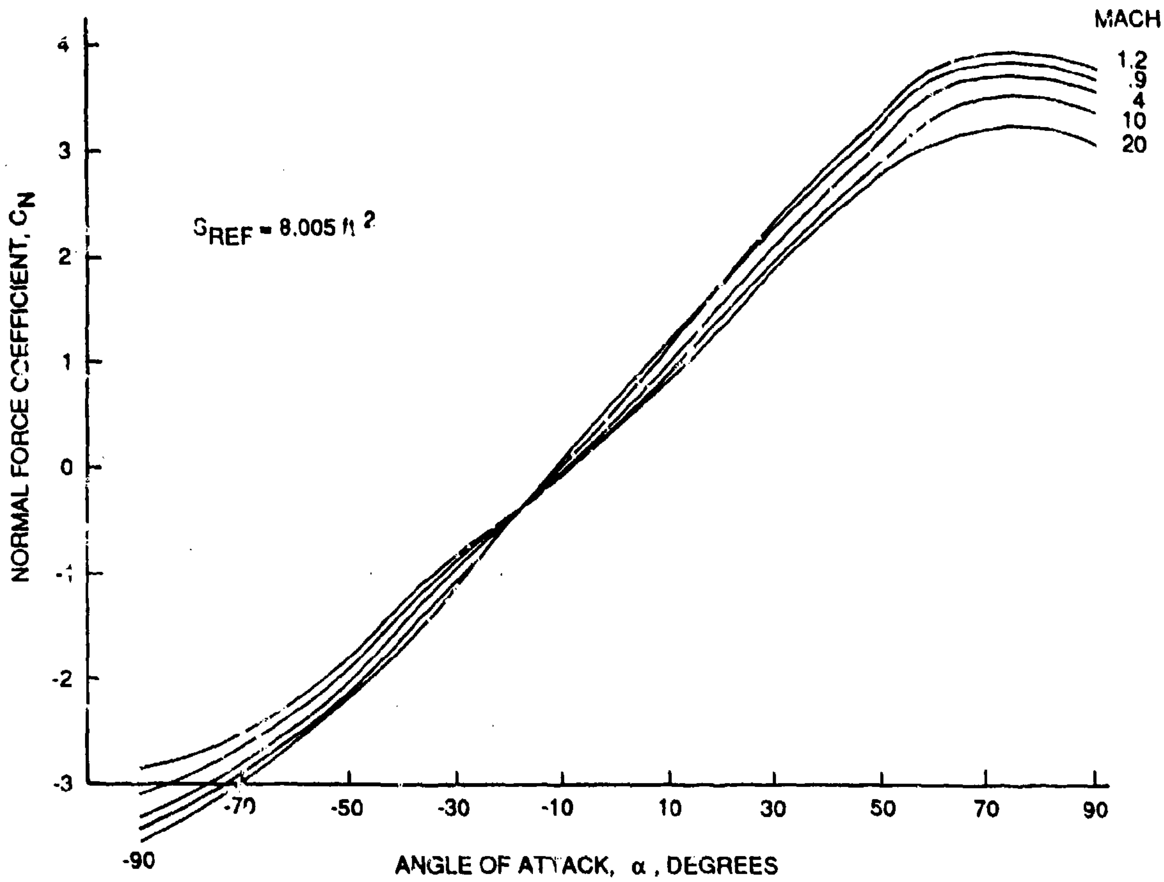


Figure 7.1-6. Normal Force Coefficient for Single-Place Encapsulated Seat

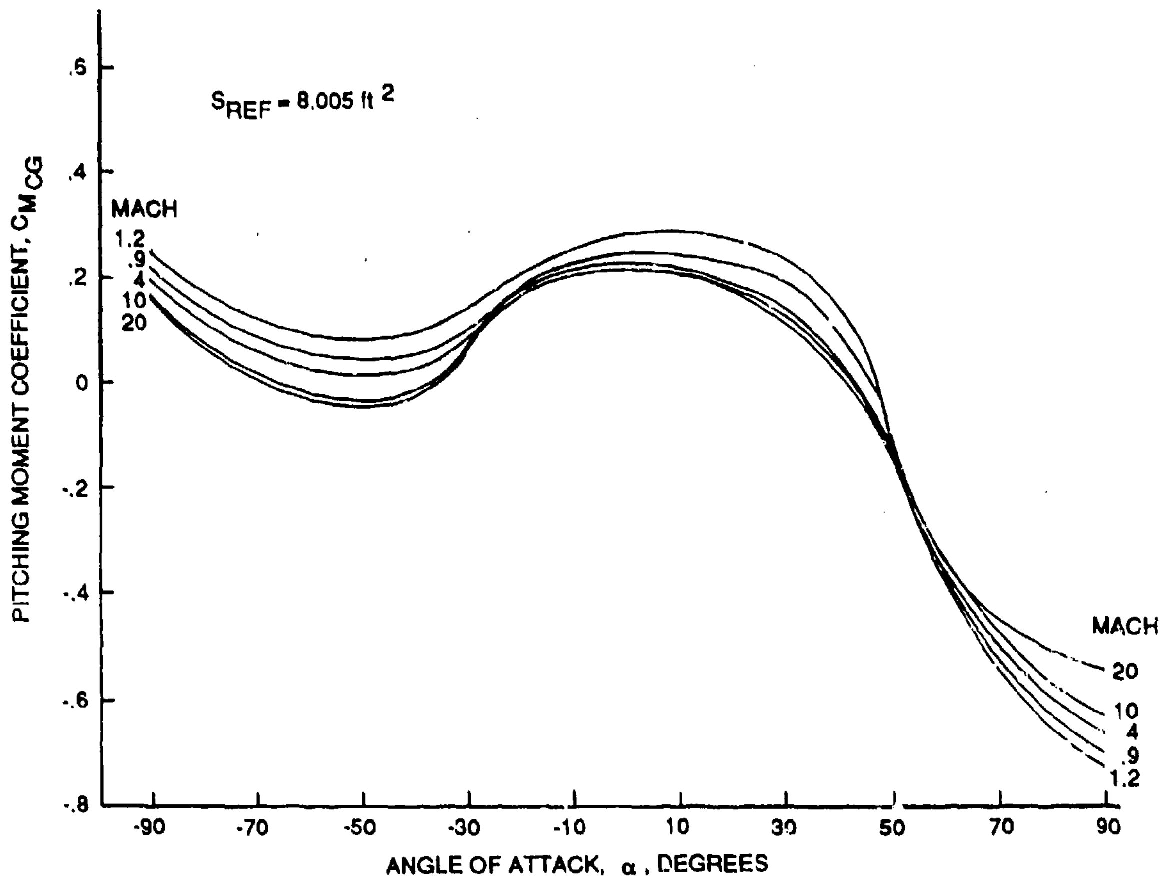


Figure 7.1-7. Pitching Moment Coefficient for Single-Place Encapsulated Seat

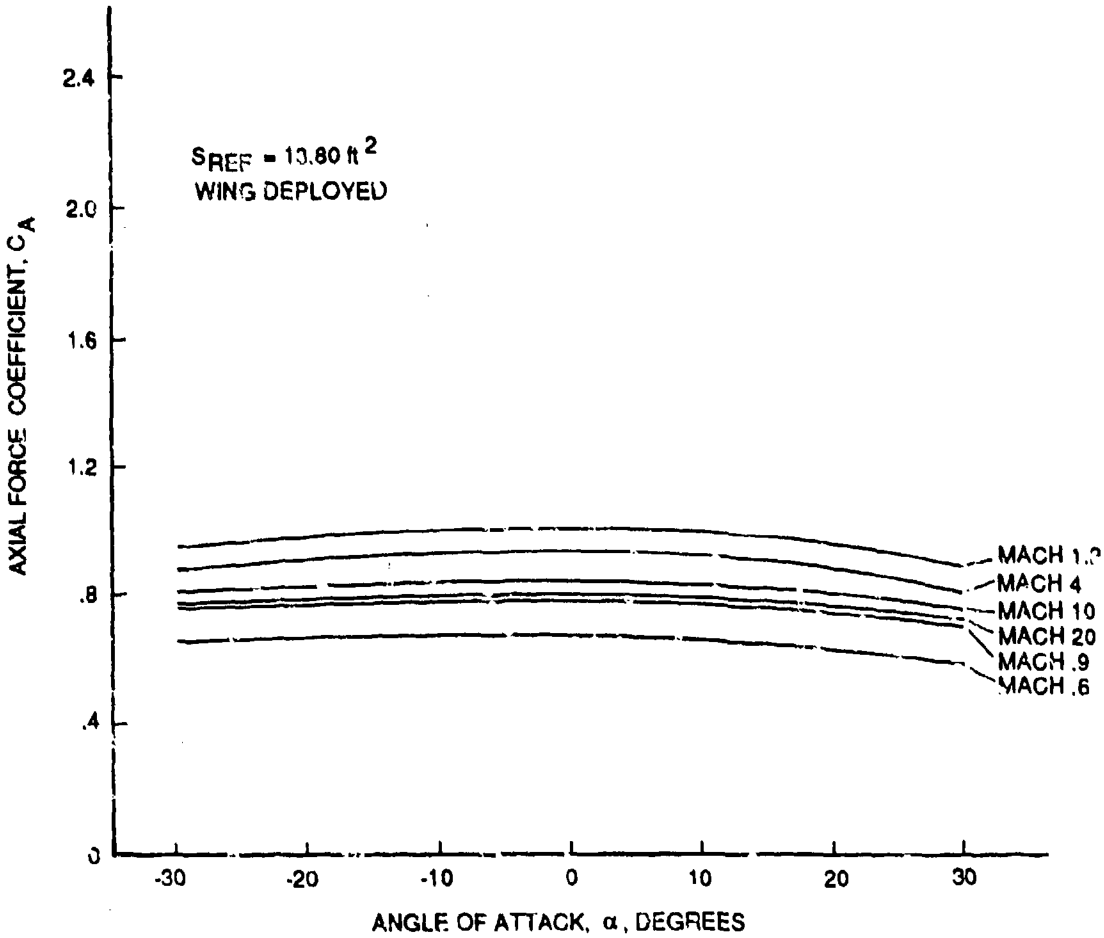


Figure 7.1-8. Axial Force Coefficient for HLV Pod Capsule with Wings Deployed

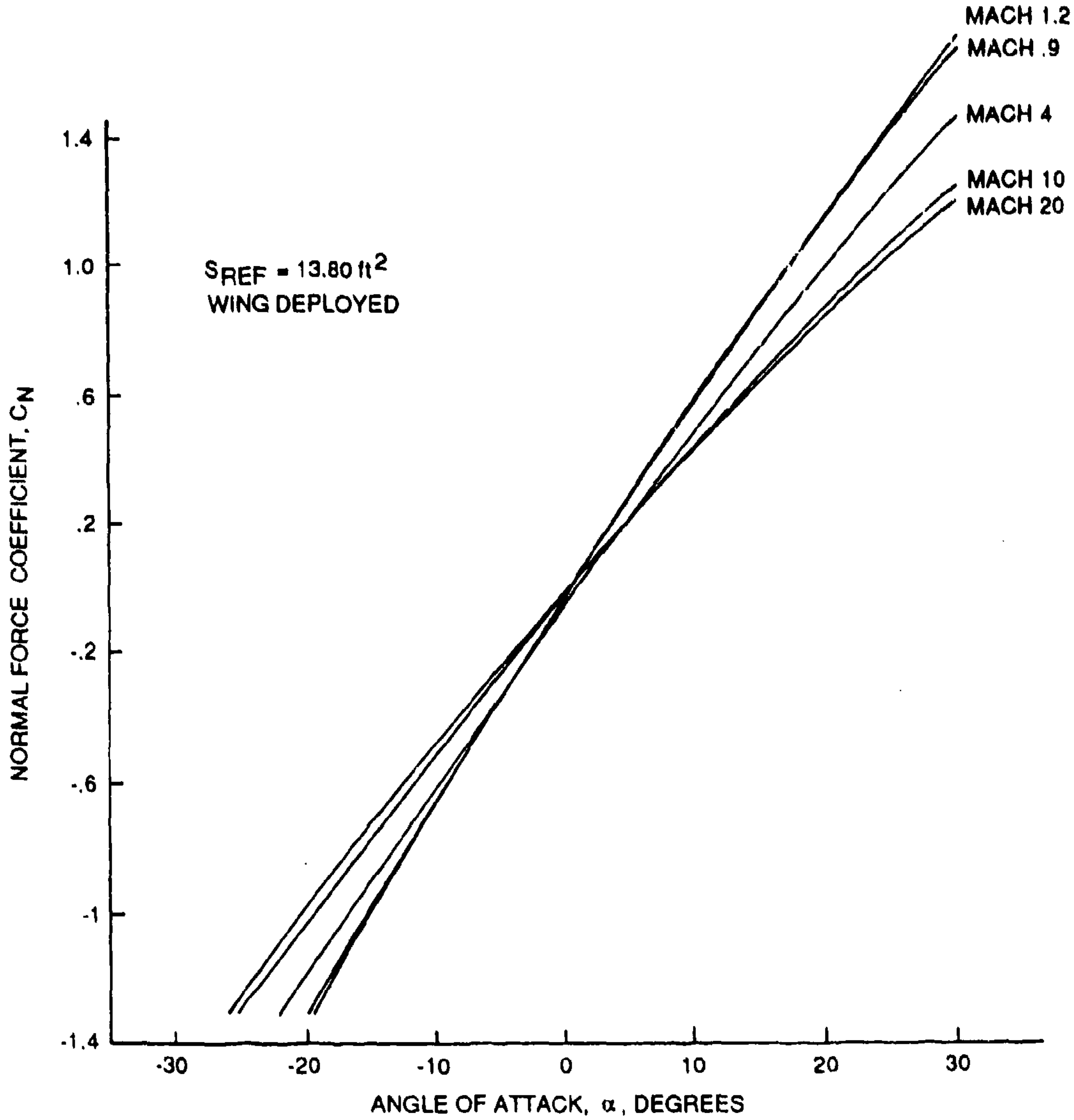


Figure 7.1-9. Normal Force Coefficient for HLV Pod Capsule with Wings Deployed

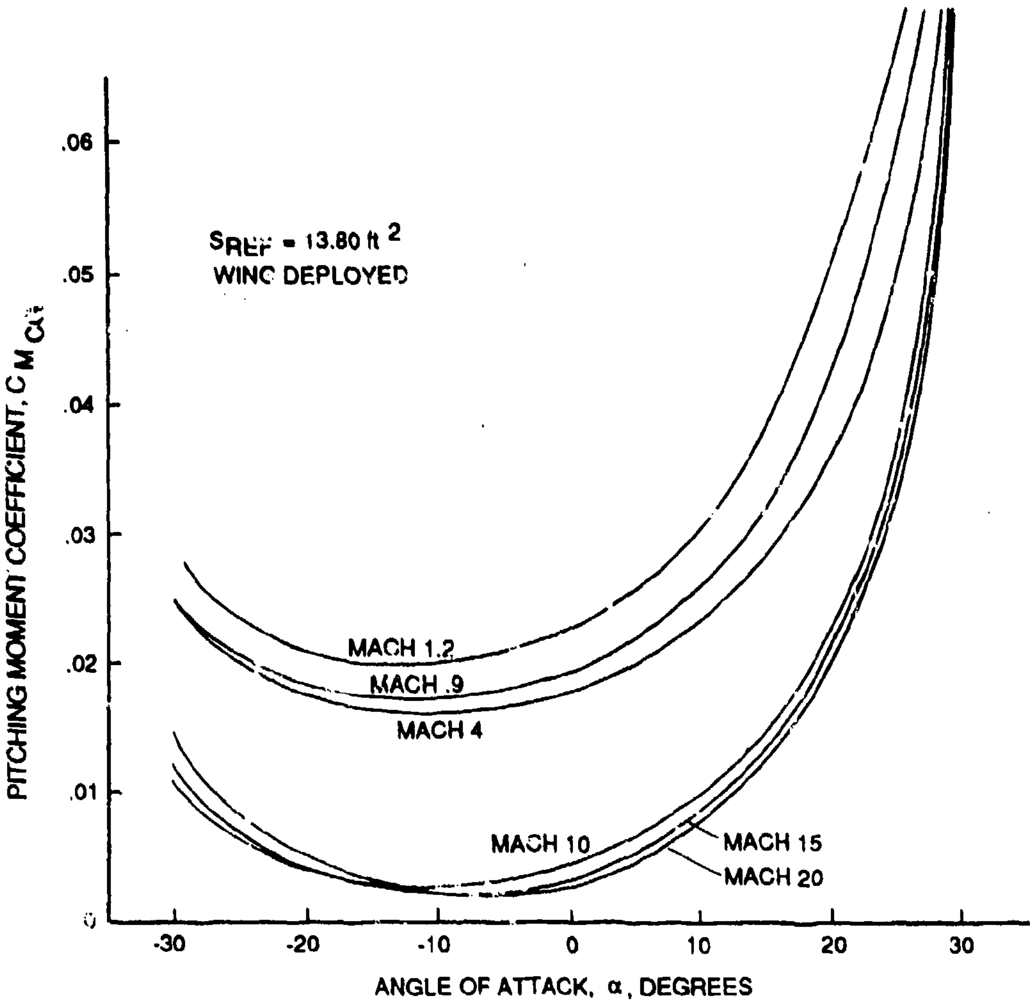


Figure 7.1-10. Pitching Moment Coefficient for HLV Pod Capsule with Wings Deployed

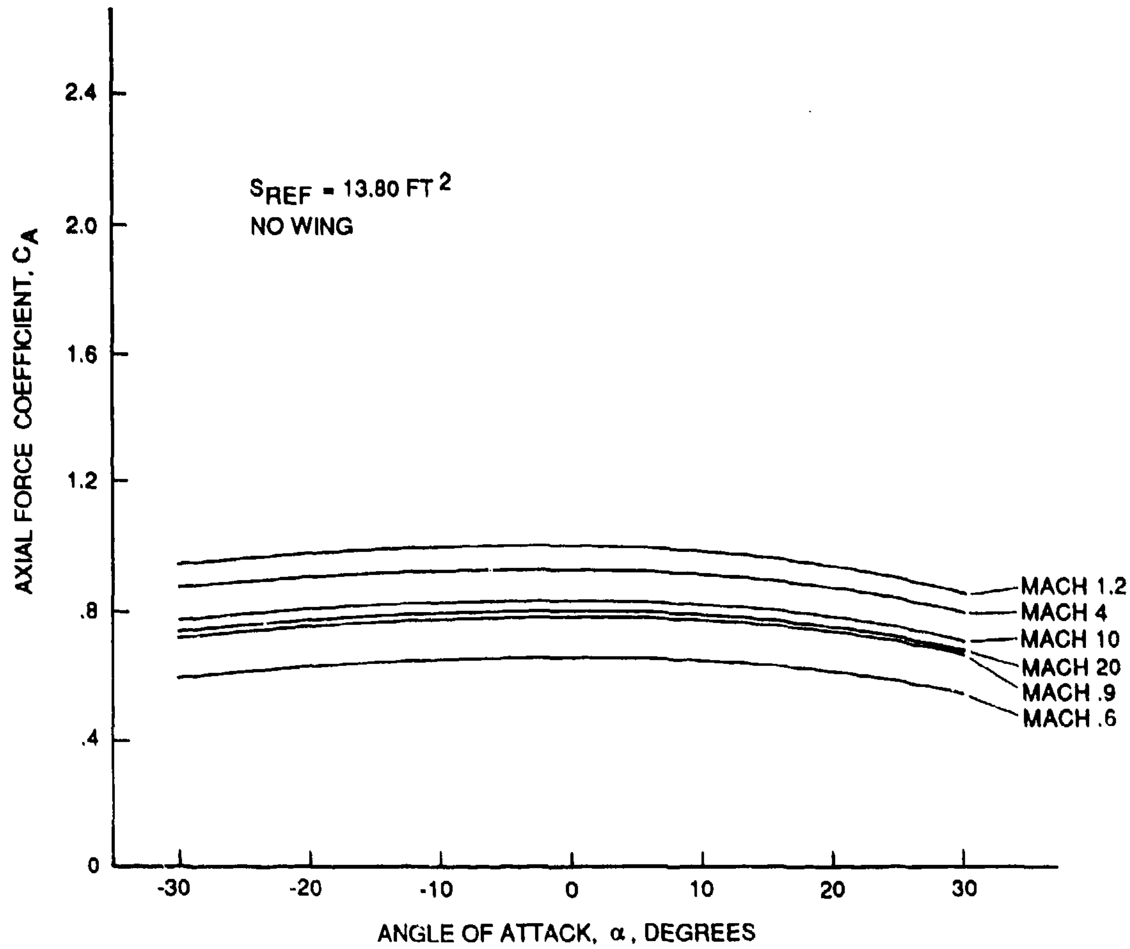


Figure 7.1-11. Axial Force Coefficient for HLV Pod Capsule with Wings Not Deployed

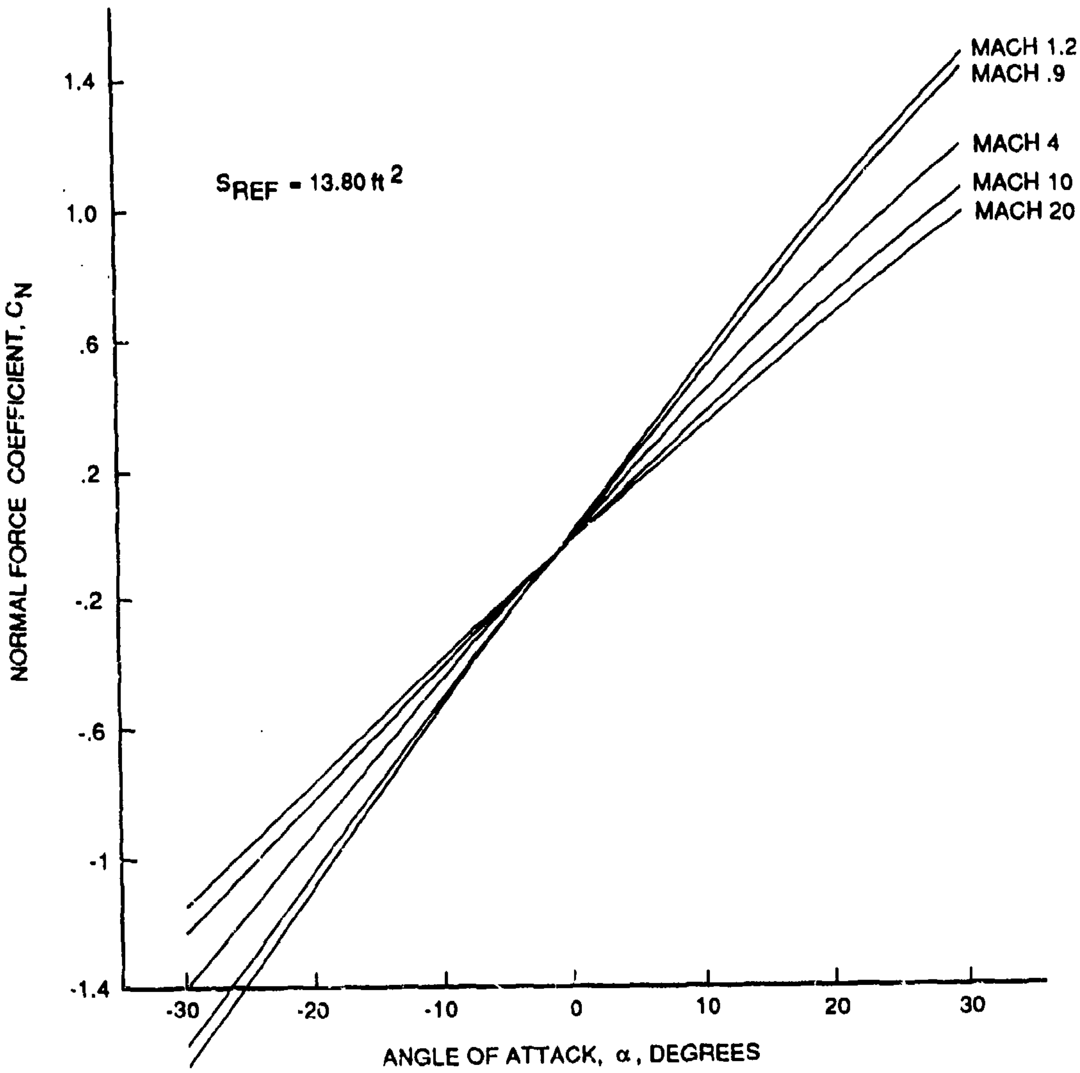


Figure 7.1-12. Normal Force Coefficient for HLV Pod Capsule with Wings Not Deployed

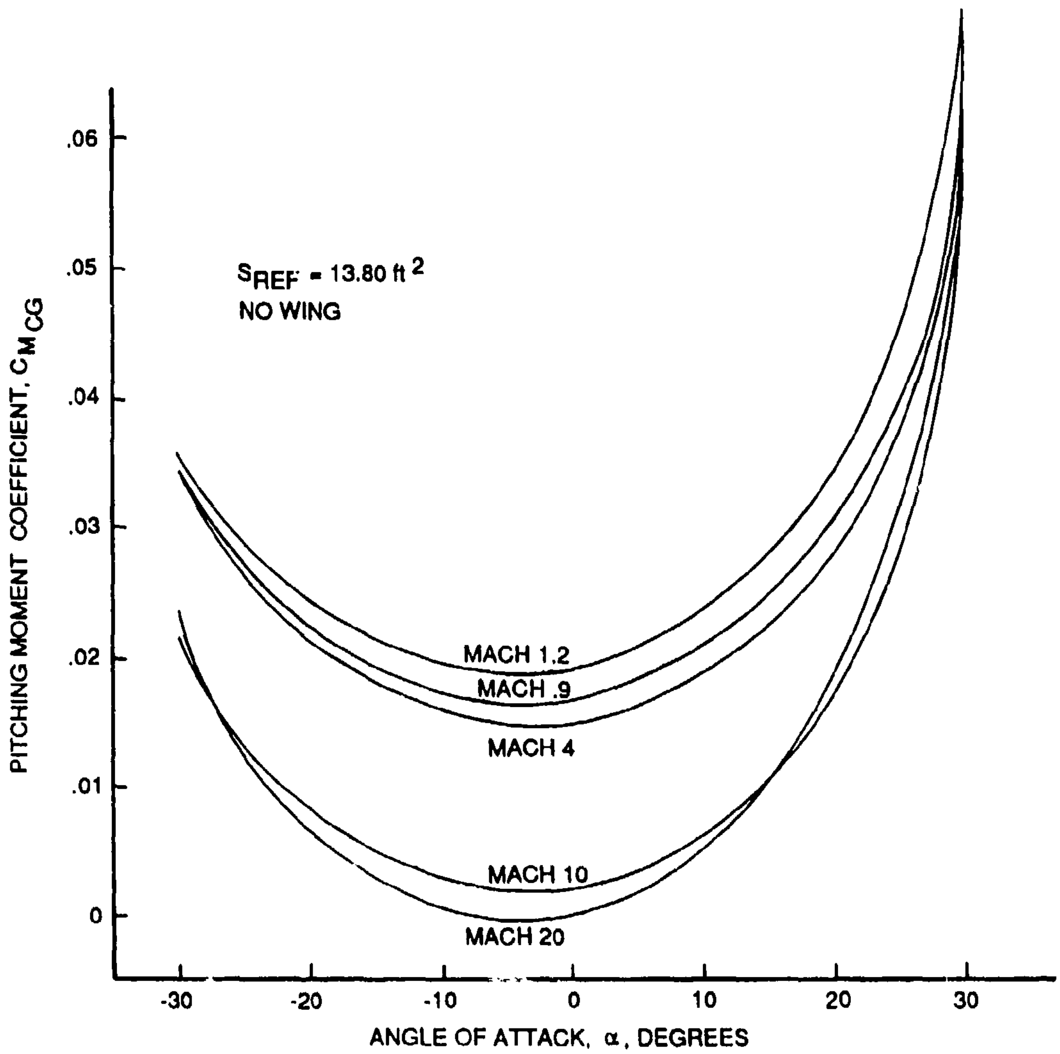


Figure 7.1-13. Pitching Moment Coefficient for HLV Pod Capsule with Wings Not Deployed

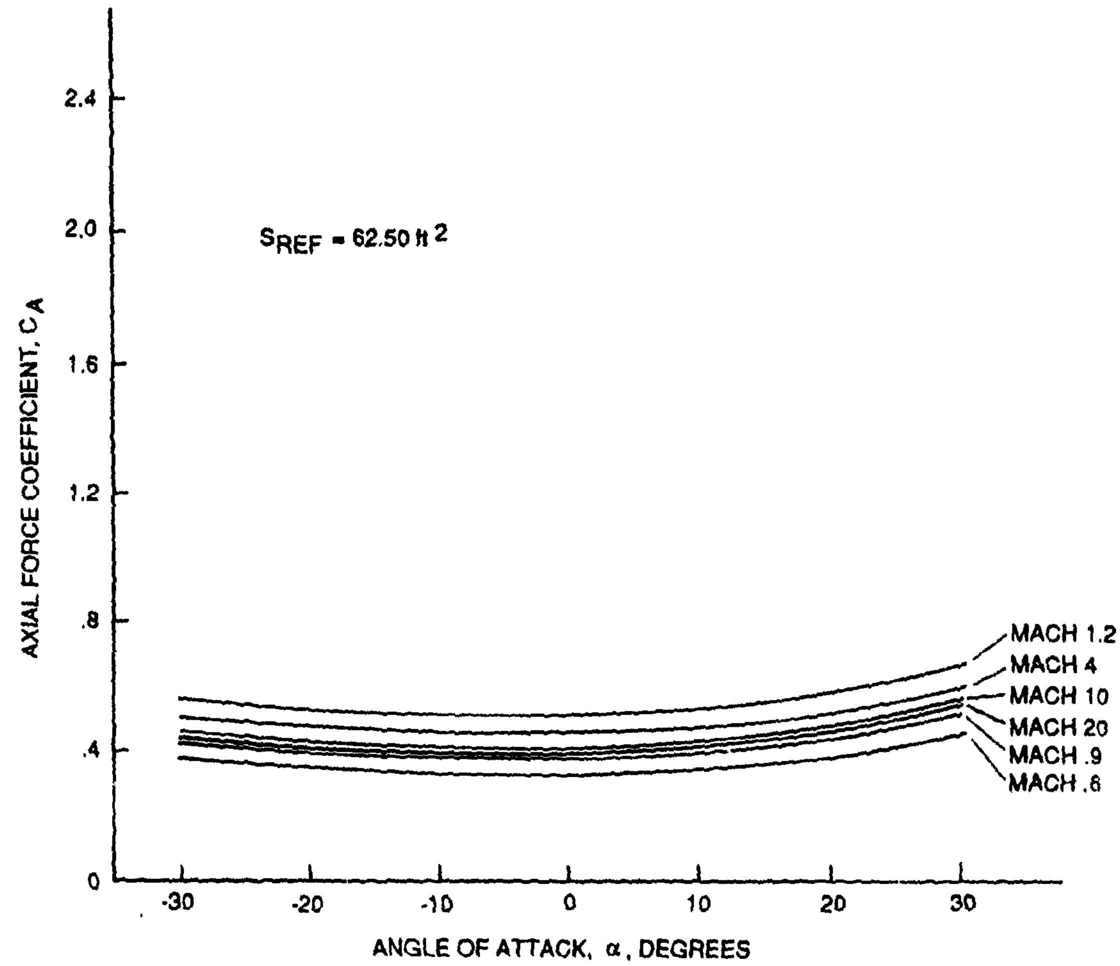


Figure 7.1-14. Axial Force Coefficient for VLV Pod Capsule

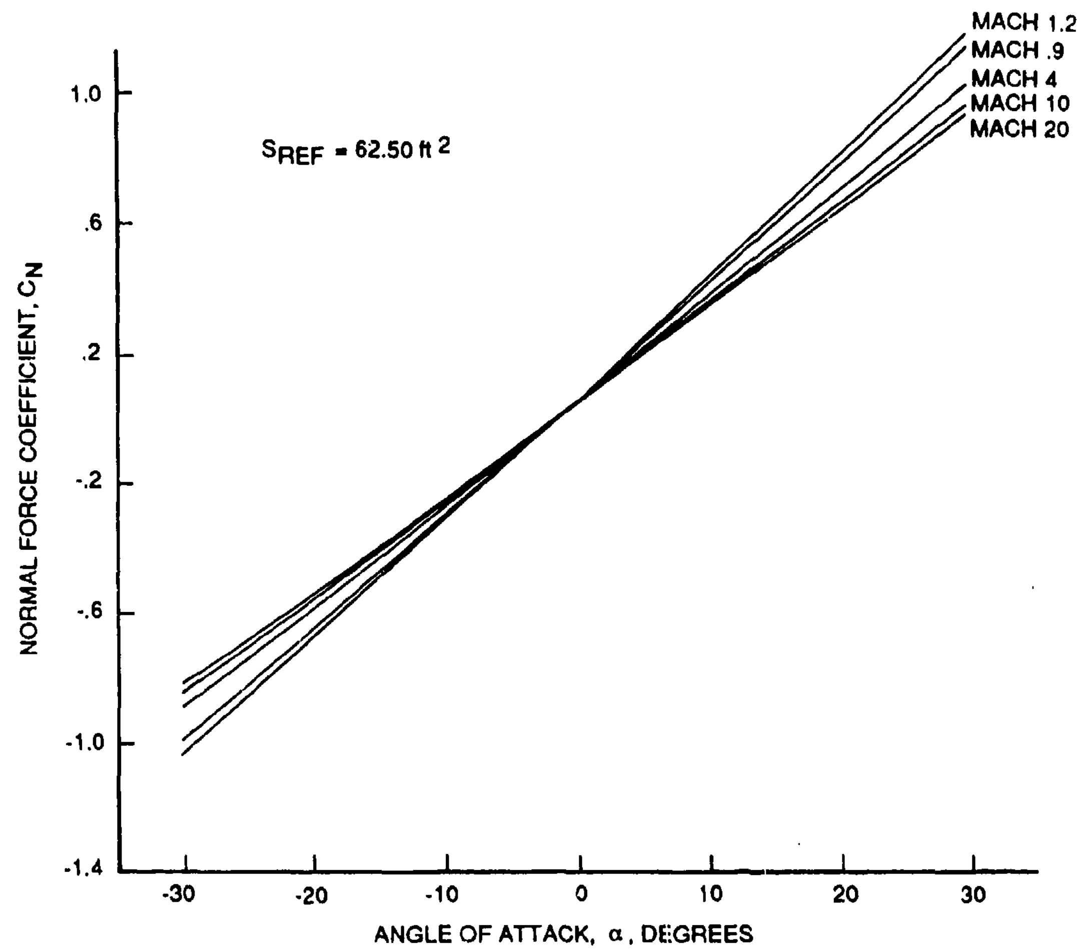


Figure 7.1-15. Normal Force Coefficient for VLV Pod Capsule

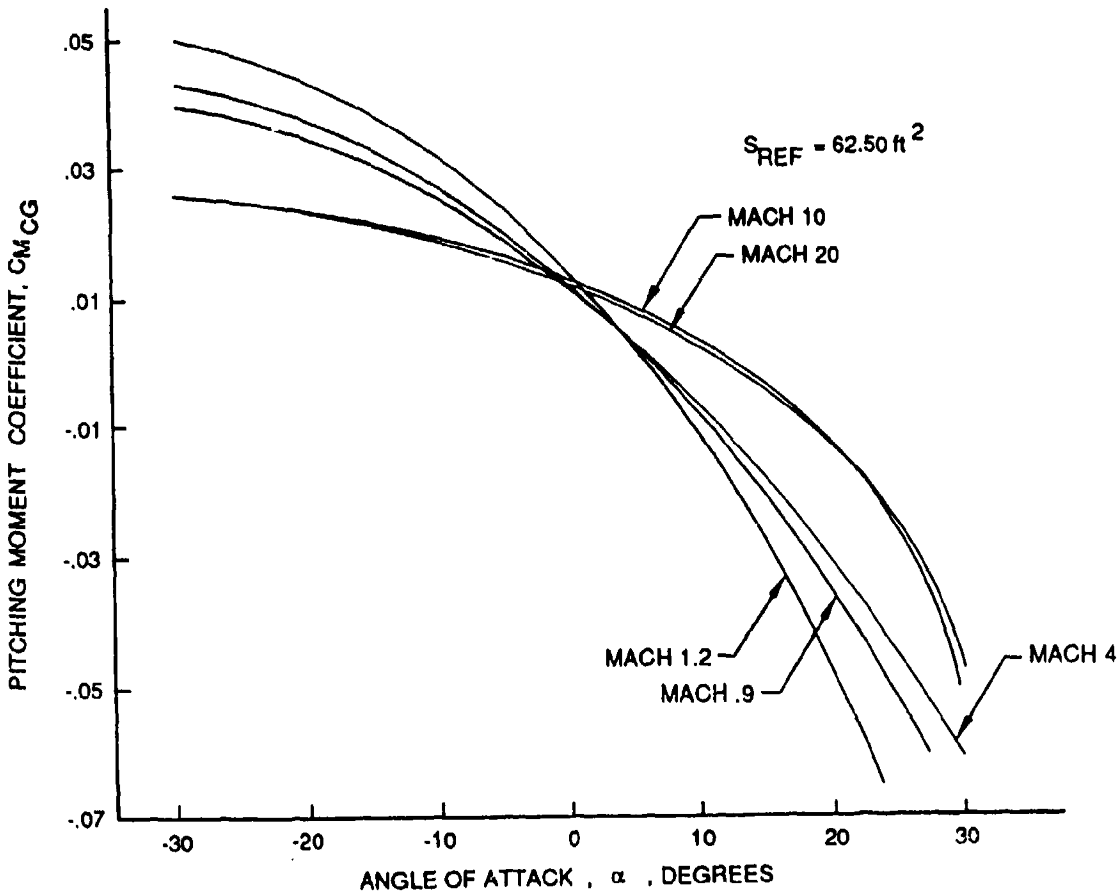
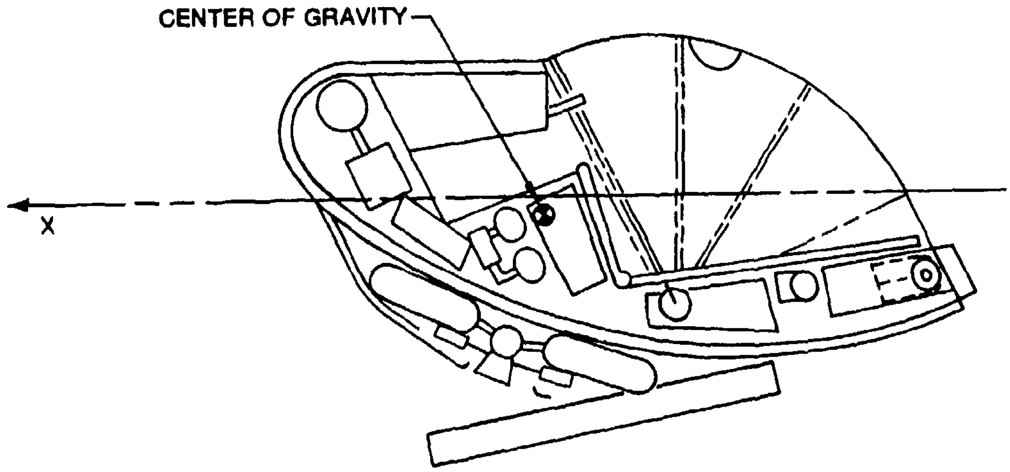
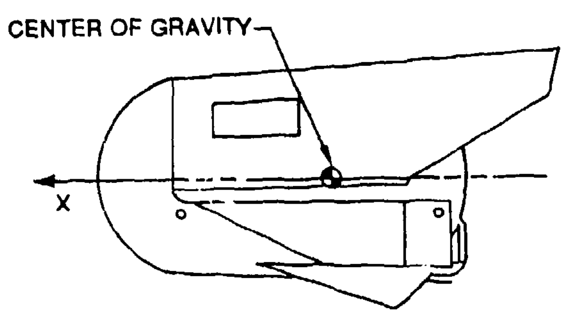


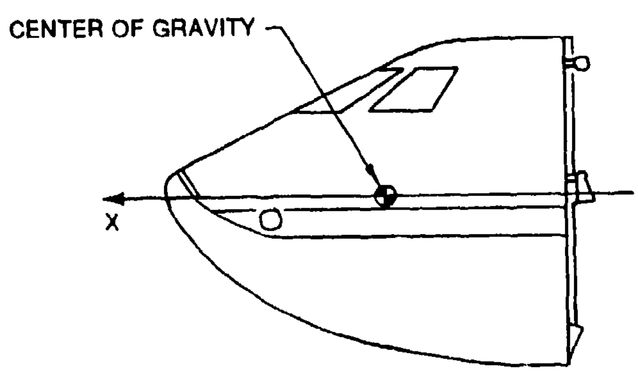
Figure 7.1-16. Pitching Moment Coefficient for VLV Pod Capsule



Encapsulated Seats



HLV Pod Capsule



VLV Pod Capsule

Figure 7.1-17. Center-of-Gravity and X-Axis Orientation Used for Aerodynamic Data

7.2 ABLATIVE MATERIAL SELECTION AND SIZING

As discussed in Section 6.2, use of a heat-shield with suitably selected ablative material was determined to be the best option for each of the four HVT escape system concepts being developed. Use of an ablative material provides an effective heat sink rate capacity per pound which is several times that for active thermal protection systems. It is also less sensitive to errors in calculated trajectories. If the heating rate is higher than calculated because of a steeper trajectory, then the ablative material is lost at a higher-than-calculated rate, but the surface is still controlled to the desired temperature. The total heat load will not change much for such a case, so that the designed ablative material thickness should still be sufficient.

Desirable characteristics of an ablative material are:

- High heat of ablation
- Low thermal conductivity
- Charing-ablator to prevent shear stress on degradation zone
- High specific heat
- High emissivity
- Low density
- Bondable to vehicle structure and insulation
- Good mechanical properties
- Low cost
- Ease of manufacture

An evaluation of the available ablative materials was done using Boeing's CHAP program. Overall material weight required for thermal protection was the prime selection criterion. The analyzed ablative materials included carbon phenolic, silica phenolic, nylon phenolic, reinforced carbon-carbon and columbium. All of these ablative materials are contained within the CHAP program.

In order to simulate the ablation processes of these materials, a re-entry trajectory of each crew escape system concept was generated by using a simple 3 degree-of-freedom EASY5 model. The highest heating rates were assumed to occur at the stagnation points of the concepts.

The heat-shields of the single and dual encapsulated heats were simulated as 6 foot radius nosecaps. The heat-shield of the HLV pod capsule was simulated as a 3.6 foot radius nosecap; and heat-shield of the VLV pod capsule was simulated as a 3 foot radius nosecap.

The CHAP program results of the ablation process at the stagnation point of the HLV pod capsule are shown in Table 7.2-1. However, these results can be somewhat misleading. The nylon phenolic material would seem to be the best ablative material on the basis of the required weight, although the total recession is significantly higher than carbon-30 phenolic or silica phenolic. However, it has a major problem in that at the high operating temperatures, its shear stress limit is low, so that the material will probably be broken apart at the expected dynamic pressures. This phenomenon is not predicted at the stagnation point (analyzed by CHAP), but will occur at other locations.

It is possible to make the thickness of Columbium less than that shown in Table 7.2-2. However, the major problem with both Columbium and carbon-carbon is the high back-wall temperature, so that while the outer heat-shield surface will be intact, it is not really protecting the rest of the structure against high temperatures.

Both silica phenolic and carbon phenolic have good ablative material characteristics. Phenolic generates a significant amount of char and the reinforced carbon and silica fiber hold the char intact during aerodynamic shear loads. As shown in Table 7.2-1, silica phenolic gave better weight per square foot, and was selected as the ablative material for the escape system heat-shields. The required thickness and other data for silica phenolic at the stagnation points of the various escape systems are summarized in Table 7.2-2.

7.3 PROPULSION SUBSYSTEM

The key issues in the propulsion subsystem design and sizing were:

a. The type of propellant to be used
b. Propulsion subsystem configuration
c. Propulsion subsystem sizing

A discussion of the above issues is presented in the following subsections.

7.3.1 Propellant Selection

As discussed in Section 6.3, gelled propellants provide significant weight advantage over the solid propellants for HVT escape system concepts. There are three reasons for this weight advantage. Firstly, the gelled propellants tend to have slightly better specific impulse than the non-metallized solid propellants. Secondly, and much more importantly, the gelled propellants allow the thrust to be variable over an approximately 10 to 1 ratio. This allows much more judicious use of the propulsive impulse over the

Table 7.2-1. Summary of Ablative Material Analyses From CHAP For Horizontally Launched Vehicle Pod Capsule

Ablative material	Maximum heat flux (BTU/ft^{2}s)	Maximum back-wall temperature (°F)	Total recession (in)	Weight per ft2 (lb/ft2)	Original thickness (in)	Remaining virgin thickness (in)
Carbon-30 phenolic	767	880	0.28	11.05	1.455	0.10
Silica phenolic	868	723	0.29	8.13	0.895	0.11
Nylon phenolic	855	790	0.62	5.83	0.92[illegible]	0.10
Carbon-carbon	842	4857	0.26	6.31	0.75	0.54
Columbium	926	4467	1.39	93.80	2.1	0.71

Table 7.2-2. Performance Summary of Silica Phenolic Ablators For Various Escape System Concepts

Escape system concepts	Maximum heat flux (BTU/ft^{2}s)	Maximum back-wall temperature (°F)	Total recession (in)	Weight per ft^2 (lb/ft^2)	Stagnation point thickness (in)	Remaining virgin thickness (in)
Single-place encapsulated seat	812	720	0.24	7.81	0.860	0.13
Dual-place encapsulated seat	752	731	0.22	7.72	0.850	0.09
HLV pod capsule	868	723	0.29	8.13	0.895	0.11
VLV pod capsule	919	721	0.32	8.31	0.915	0.12

large time during which attitude control must be maintained by reaction jets. Thirdly, the associated propulsion hardware weight tends to be significantly less for the gelled propellants because of the associated lower-weight fuel/oxidizer tubes to the reaction jets instead of the higher-weight gas manifolds associated with solid propellants.

There are many concerns regarding gelled propellant behavior under some operating conditions (high shear rates, moisture, contamination), toxicity, incompatibility with many materials and hardware development status. A detailed trade study between the gelled and the solid propellants considering all these design factors was recently conducted on the ACECT program (Reference 1). This trade study showed the overall superiority of gelled propellants. This superiority of gelled propellants was estimated to be even greater for HVT escape system application due to the larger time over which the reaction jets must operate at less-than-maximum thrust. The gelled propellants were, therefore, selected over the solid propellants for HVT escape system concept.

At a later stage in the study, a cryogenic propulsion system using liquid hydrogen and liquid oxygen was designed for the HLV pod capsule application and compared with the gelled propellant system. The cryogenic system used monopropellant hydrazine gas generator instead of cold gas for system pressurization to 3000 psi with relatively lower weight. The hardware weight was estimated on the basis of an existing Rocketdyne engine design. The overall propulsion system weight for the HLV pod capsule was estimated to be 2822 pounds using cryogenics, compared with 943 pounds estimated for gelled propellants. Cryogenic propulsion systems were, therefore, not considered for HVT escape system application any further.

7.3.2 Propulsion Subsystem Configuration

Based upon the propulsion subsystem configuration studies conducted on the ACECT capsule program (Reference 1) and the CREST demonstration ejection seat program (Reference 2), the propulsion subsystem for each of the HVT escape system concepts was designed to have the following characteristics:

a. Two main side-by-side nozzles with ± 15 deg thrust-vectoring capability in pitch.
b. Three pairs of reaction jets to provide attitude control in pitch, roll and yaw.

The locations of the nozzles and the reaction jets are shown in Figure 5.1-1 for encapsulated seats, Figure 5.3-2 for HLV pod capsule, and Figure 5.4-2 for VLV pod capsule.

A key question in the location of the main nozzles was whether they could be suitably located over the heat shields, and then discarded when these are not needed anymore, without affecting the integrity of the heat shields. Four possible methods of accomplishing this are discussed below.

7.3.2.1 Attachment Using Straps

The Mercury space capsule had its retrorockets strapped over the heat shield. The thrust vector was normal to the heat shield surface, which carried the loads to the capsule structure. The straps only held the rocket package in position. The encapsulated seats have a similar arrangement. The major complication is that the seats will have to be able to operate at high Mach numbers within the atmosphere, subjecting the propulsion pallets to high levels of aerodynamic pressure and heating. Since the propulsion phase typically lasts about one second under these conditions, and the pallet is then immediately jettisoned, strap burnthrough should not be a problem provided heat resistant materials or ablative coatings of sufficient thickness are used.

Use of straps on the HLV pod capsule would be more complicated since two thruster pods are required and the blunt nose of the heat shield makes placement of "+x" axis straps more difficult, but still possible. Possible strap arrangements are shown in Figure 7.3-1.

7.3.2.2 Attachment With Bolts

A less conventional approach is to bolt the pallet directly to the capsule structure through the heat shield using frangible bolts. While this provides a secure but separable attachment, it compromises the heat shield, a major concern during hypervelocity escapes. A metal or reinforced carbon-carbon bolt would provide a heat conduction path through the heat shield, especially since the severed end of the bolt would create a hot spot due to its surface roughness and lack of ablative cooling. Besides conducting heat to the capsule structure, the heat shield ablative near the bolt could be damaged by the heat, causing gaps that would increase spot heating and allow the hot gas to damage the capsule structure.

7.3.2.3 Attachment With Hook and Bonding

In this approach, suited particularly for HLV pod capsule, there are separate provisions for transmitting the two main thrust vector components: one upward or normal to the heat shield surface; and one forward along the "x" axis. The upward loads

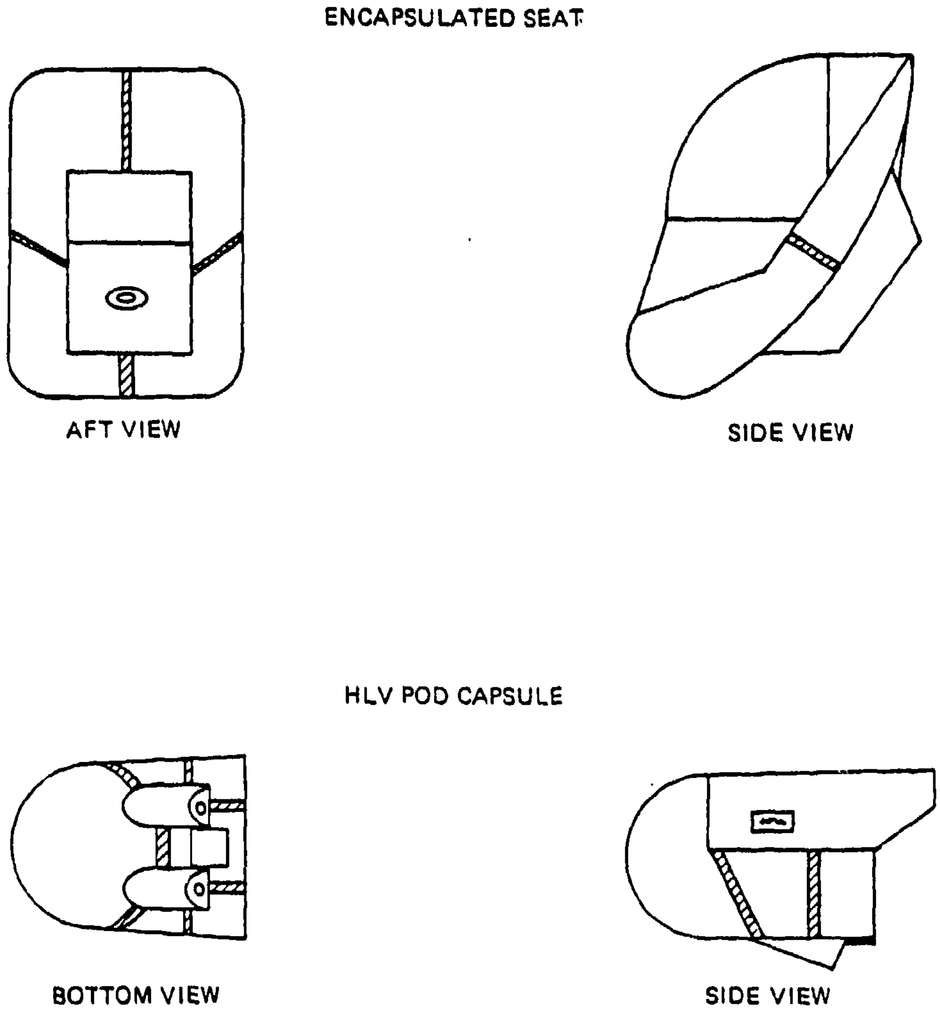


Figure 7.3-1. Strap Attachment Arrangements

are carried through the heat shield to the capsule structure and the forward loads are carried to the aft capsule structure through a member that also houses the thruster propellant lines, as shown in Figure 7.3-2. During the propulsion phase of an escape sequence, this member is in tension and the forward thrust component is transferred to the capsule structure through a hook arrangement. The much smaller lateral loads and the weight of each thruster pod during normal operations are carried by a bonded attachment fixture and pyrotechnically frangible bolt.

The attachment fixture, as shown in Figure 7.3-3, consists of a mounting pad composed of teflon, phenolic or similar polymer bonded directly to the heat shield, a metal nut plate attached to this pad by screws or some similar fastener, and the frangible bolt supporting the thruster connected to the nut plate. A longitudinally slotted bolt hole is used in the thruster pod to ensure that the large forward loads are carried through the tension member and not the bonded surface.

During the propulsion phase (see Figure 7.3-2), the attachment fixture is protected from aerodynamic heating by the thruster pod structure. After separation, the mounting pad burns away until the heat shield is exposed. A similar approach has been proposed to mount the ejection rail slipper blocks for the vertically launched vehicle (VLV) escape pod.

7.3.2.4 Fixed Pallets

The final attachment approach is to integrate the propulsion system into the re-entry capsule. Under this concept the propulsion system is protected under the heat shield and cannot be jettisoned. The complexity of an attachment and jettison mechanism is thus avoided.

Such an integrated system would require a reconfiguration of the escape capsules to delete the protruding nature of the current propulsion systems, which would result in projecting, small-radius areas on the heat shield leading to unsatisfactory aerodynamics and probable hot spots. The encapsulated seat and HLV pod configurations would also require thruster exhaust ports through the heat shield. These could become hot spots during aerodynamic heating as well as allow heat to leak past the heat shield. This would require the addition of an active cooling system or ablative liner to the thruster nozzles. Retaining the propulsion system components would also require increased recovery and impact attenuation system capability.

The proposed VLV pod capsule does, however, use an integrated propulsion system, which is feasible for this configuration since the required thrust vector does not pass

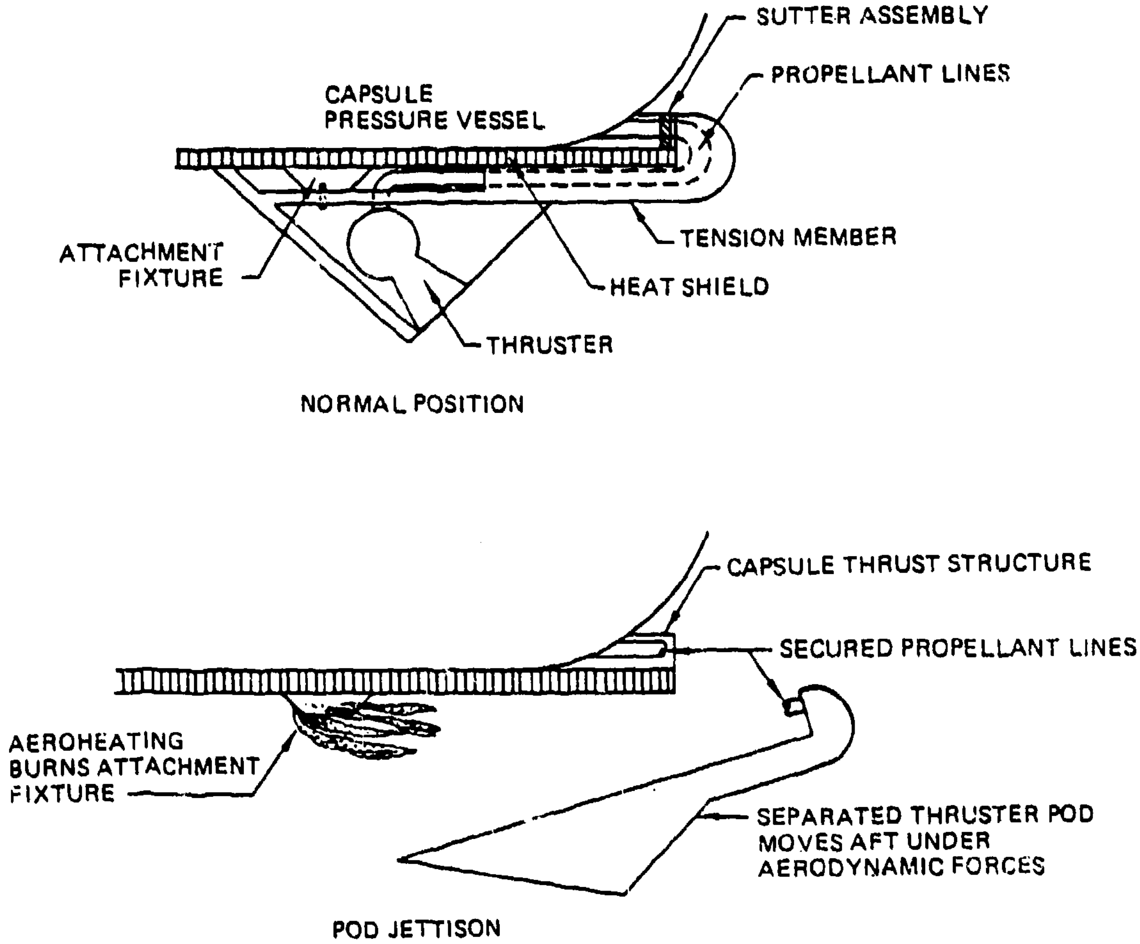


Figure 7.3-2. Thruster Pod Attachment and Jettison

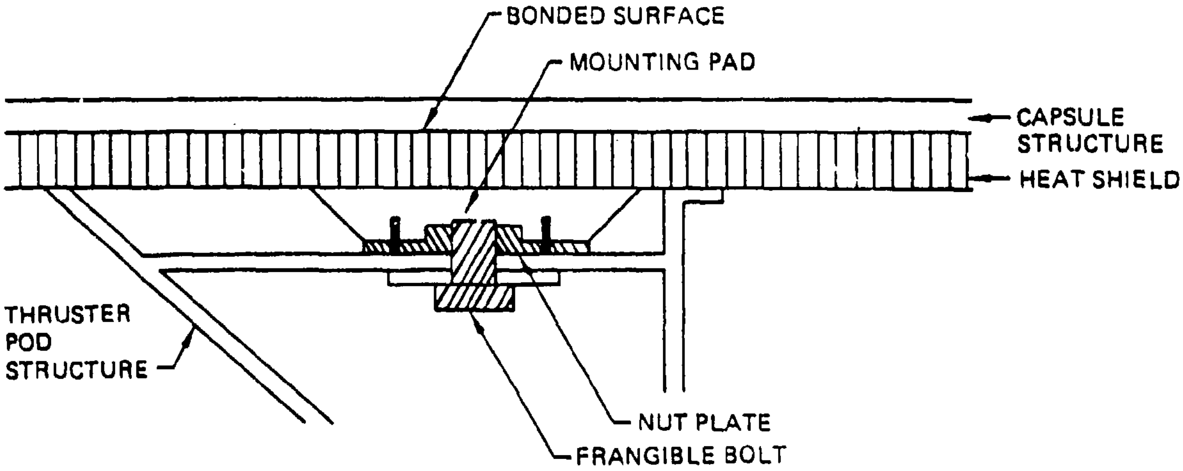


Figure 7.3-3. Bonded Attachment Fixture

through the heat shield, and the crew ejects from the capsule, which is not recovered, before ground impact.

7.3.3 Propulsion Subsystem Sizing

The main nozzle thrust for any HVT escape system concept should be sufficient to get the escape system away from the vehicle fast enough even under high dynamic pressure conditions, so that it does not hit any part of vehicle structure. ACECT capsule study (Reference 1) showed that a thrust to ejected capsule weight ratio of 11.5 was sufficient for it to avoid hitting the vehicle at dynamic pressure up to 2750 psf and pitch rate up to -30 deg/sec. The maximum dynamic pressures for the HLV and the VLV are only 2000 and 400 psf respectively. Thus, a nozzle thrust to escape system weight ratio was taken tentatively to be equal to 10. It was proven to be sufficient by subsequent performance analysis for other escape conditions of interest. It should be noted that a further reduction in thrust will not have significantly affected the propulsion system weights. The calculated thrusts for various HVT escape system concepts are shown in Table 7.3-1.

The impulse requirements for the main nozzle propulsion systems are governed by the maximum velocity change required for the deorbit maneuver. This velocity change requirement was determined to be 428 ft/sec. It allows deorbit maneuver from orbits up to 300 nautical miles above the earth's surface. The calculated impulse levels are shown in Table 7.3-1. The corresponding values of propellant weight, propulsion system weight, nozzle throat area, fuel tank volume, and oxidizer tank volumes are also shown in Table 7.3-1.

The thrust per pair of reaction jets was kept at a relatively low value to avoid large weight of the attitude control system. Subsequent performance analysis showed that the thrust levels for reaction jets shown in Table 7.3-1 were sufficient for low altitude, adverse attitude conditions, provided that the control gains were tuned accordingly. The impulse levels and the corresponding propellant weights are determined by the hypersonic escape condition, where attitude control system must maintain the stability of the escape system until the speed falls to Mach 4, where a drogue can be deployed. A reduction in speed from Mach 20 to Mach 4 at an average deceleration level of 8 g's requires about 62 seconds. The average reaction jet thrust should be quite small at about 10 percent, if the attitude control system is designed properly. The corresponding values of required impulse, propellant weight, propulsion system weight, fuel tank volume and oxidizer tank volumes are shown in Table 7.3-1.

Table 7.3-1. Propulsion Subsystem Data

Parameters	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
For main nozzles				
Total thrust, lb	17650	55940	10100	24330
Total impulse, lb - sec	22800	72400	13100	31600
Throat area, in^2	1.95	6.29	1.16	3.12
Propellant, lb	91	290	52	126
Propulsion system weight, lb	228	724	131	316
Fuel tank volume, in^3	870	2763	500	1206
Oxidizer tank volume, in^3	708	2249	407	982
For reaction jets				
Thrust per pair, lb	1250	2000	1000	1670
Impulse per pair, lb - sec	22750	36500	18250	30500
Throat area, in^2	0.26	0.42	0.21	0.35
Propellant, lb	91	146	73	122
Propulsion system weight, lb	137	219	110	183
Fuel tank volume, in^3	868	1393	696	1164
Oxidizer tank volume, in^3	707	1134	567	948

7.4 LIFE SUPPORT SYSTEM

The life support system must provide sufficient oxygen to the crewmembers and maintain the desired pressure in the capsule or the encapsulated seat during emergency escape. The maximum period for which the life support must be provided is governed by the time for which the escape vehicle may have to stay in orbit before a deorbit maneuver can be executed, which will bring the crewmembers back to continental United States (CONUS).

Figures 7.4-1 and 7.4-2 show the trajectory footprints for 35 degrees and 90 degrees circular orbits overlaid on the geographic maps of earth. These show that in the worst case, corresponding to 90 degrees orbit, the escape vehicle may have to wait for 4 orbits around the earth before a deorbit maneuver can be executed to bring the crewmember back to CONUS. A life support system design for 6 hours will allow for this waiting time in orbit and the time required to reach 15,000 feet altitude above ground.

The various calculated data for the life support system are summarized in Table 7.4-1. These are based on oxygen requirements of 15 lpm, BTPS per crewmember combined with crew size and crew activity multiplier factors. Also, per MIL-D-19326G, it was assumed that the design quantity of liquid oxygen (LOX) available to crewmembers following the LOX converter fill is only 86 percent of the converter size. The gases exhaled by the crewmembers are sufficient to keep the pod capsule or the encapsulated seat pressurized to 8 psi if the leakage is designed to be better than the values shown in Table 7.4-1.

7.5 WEIGHT AND INERTIAL PROPERTIES

The estimated subsystem weights and locations for the dual-place encapsulated seat, HLV pod capsule, single-place encapsulated seat, and VLV pod capsule are listed in Tables 7.5-1, 7.5-2, 7.5-3, and 7.5-4 respectively. The composite inertial properties for the four escape concepts are summarized in Table 7.5-5.

The selection of the ablative materials and the corresponding heat shield weights are discussed in Section 7.1. The insulation under the heat shield was taken as Min-k 2000 (made by Monville), which weighs 0.8 lbs/ft^2. The propulsion system and life support system sizing and weights are discussed in Sections 7.2 and 7.3 respectively. The basis for other subsystem weights are discussed in the following paragraphs.

The HLV and the VLV pod capsule structural weights were based upon the data available for the two vehicles. The structural weights of the encapsulated seats were estimated on the basis of the B-58 encapsulated seat weight.

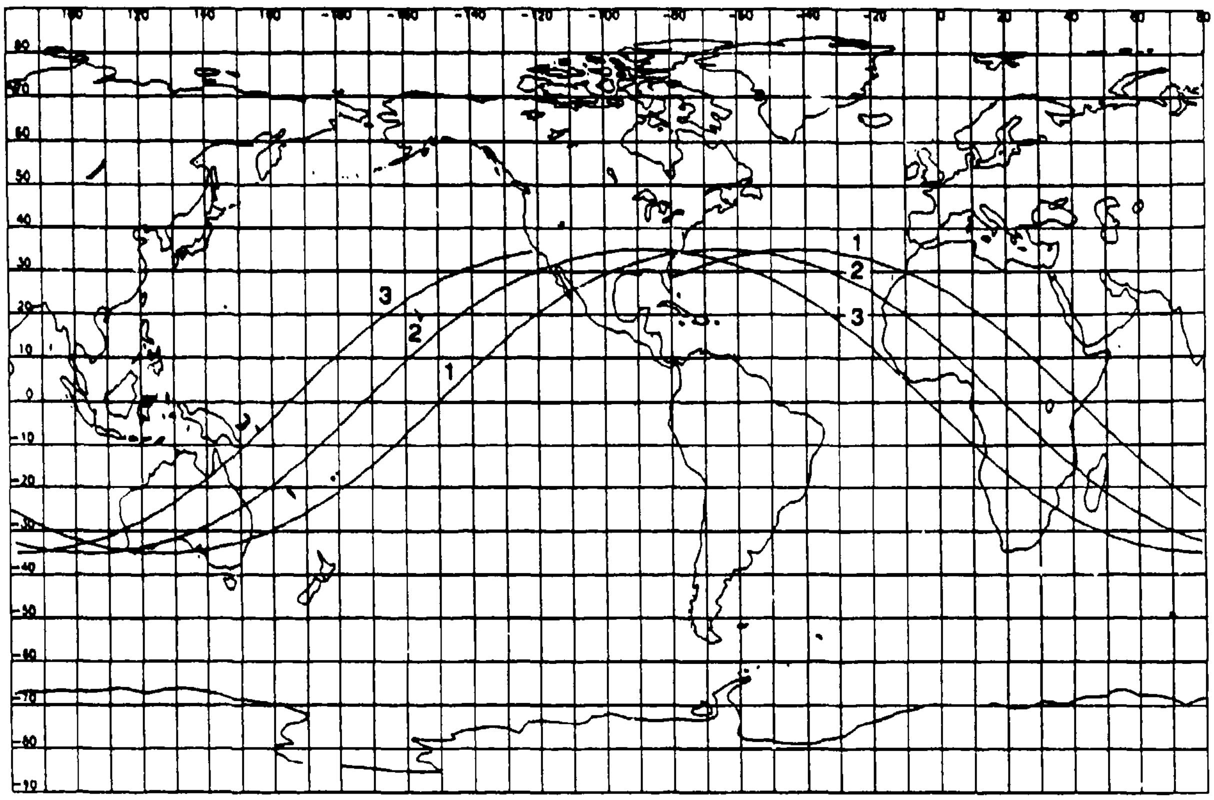


Figure 7.4-1. Trajectory Footprint for 35 Degree Inclination Circular Orbits

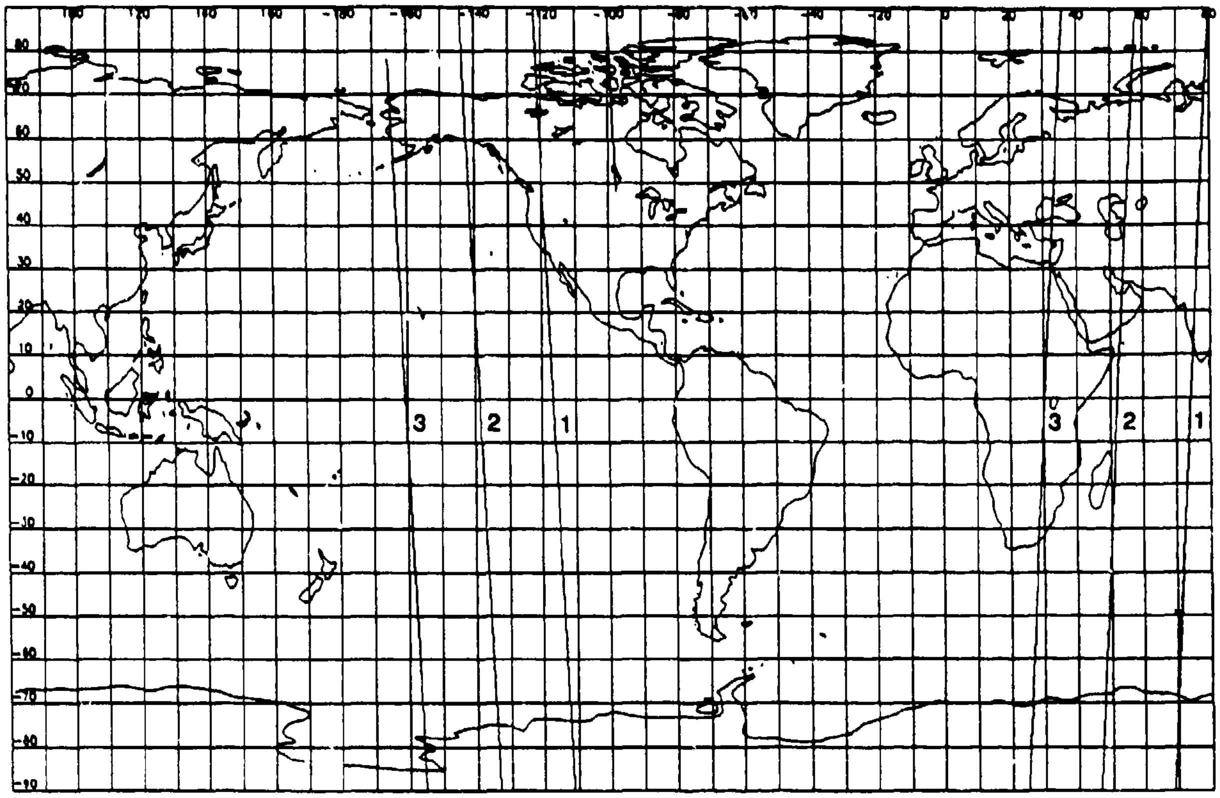


Figure 7.4-2. Trajectory Footprint for 90 Degree Inclination Circular Orbits

Table 7.4-1. Life Support System Data

Parameters	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Total volume, cu ft	56	405	29	444
Net volume, cu ft	34	284	17	311
Estimated leakage, lb_m/hr	0.80	0.13	0.50	0.13
Liquid oxygen required, liters	8.06	8.06	4.40	4.40
Pilot exhalation, lb_m/hr	1.58	1.58	0.79	0.79
Oxygen system weight, lb	43	43	28	28

Table 7.5-1. Dual-Place Encapsulated Seat Subsystem Weights at Ejection

Component	Weight (lb)	Positions	
		X - (in)	Z - (in)
Structure	220	28	26
Separation cutter	5	-	-
Jettison escape hatch (pyrotechnic)	5	-	-
Instruments	40	10	25
Ejection rail	50	-	-
Catapult outer tubes	18	49	32
Pilots – 2 (99 percentile)	578	28	34
Life support (6 hours)	43	8	5
Main propulsion system	228	37	14
Attitude control system	137	28	22
Recovery system	53	49	57
Heat shield/insulation	260	25	21
Power supply (battery)	20	7	15
Door	62	21	41
Catapult inner tube/propellant	50	-	-
Survival kits	60	27	20
Controller/sensors	15	7	15
Inertial reels/body harness	30	41	37
Totals	1875	28	27

Table 7.5-2. HLV Pod Capsule Subsystem Weights at Ejection

Component	Weight (lb)	Positions	
		X - (in)	Z - (in)
Structure	480	81	0
Forward avionics	300	23	0
Aft avionics	500	109	0
Furnishings	488	57	2
ECS	920	52	-26
Separation system	22	-	-
Escape hatch pyrotechnic system	4	76	34
Pilots - two (99 percentile)	578	66	5
Life support (6 hours)	43	28	-24
Main propulsion system	724	109	-37
Attitude control system	219	106	-25
Recovery system	167	162	32
Heat shield/insulation	877	32	-22
Wings/actuation system	118	84	-10
Power supply (battery)	20	80	-12
Survival kit	62	62	-08
Controller/sensors	25	80	-13
Flotation system	67	72	-15
Totals	5614	70	-13

Table 7.5-3. Single-Place Encapsulated Seat Subsystem Weights at Ejection

Component	Weight (lb)	Positions	
		X - (in)	Z - (in)
Structure	110	28	27
Separation cutter	5	-	-
Jettison escape hatch (pyrotechnic)	4	-	-
Instruments	20	12	25
Ejection rail	36	-	-
Catapult outer tube	13	50	18
Pilot (99 percentile)	289	34	36
Life support (6 hours)	28	29	22
Main propulsion system	131	40	15
Attitude control system	110	12	11
Recovery system	28	51	57
Heat shield insulation	170	27	18
Door	40	26	50
Power supply (battery)	10	9	18
Catapult inner tube/propellant	38	-	-
Survival kit	30	31	27
Controller/sensors	16	9	18
Inertial reel/body harness	15	47	46
Totals	1093	30	26

Table 7.5-4. VLV Pod Capsule Subsystem Weights at Ejection

Component	Weight (lb)	Positions	
		X - (in)	Z - (in)
Structure	400	30	5
Instruments, ECS, avionics	350	54	0
Separation system/pyrotechnic system	11	-	-
Separation cutter	5	-	-
Ejection slide rails	50	-	-
Escape natch/pyrotechnic system	4	0	-43
Pilot (99 percentile)	289	0	4
Extraction system/seat	110	36	-12
Life support system (2 hours)	28	48	24
Main propulsion system	316	32	36
Attitude control system	183	32	36
Drogue parachute	28	7	-36
Heat shield/insulation	610	60	32
Slide blocks	30	41	43
Survival kit	40	31	12
Power supply (battery)	20	36	24
Controller/sensors	25	36	24
Totals	2499	44	17

Table 7.5-5. Composite Inertial Properties Of HVT Escape System Concepts at Ejection

Parameters	Duai-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Ejected weight, lb	1875	5614	1093	2499
Center-of-gravity location, x, y, z; in	28 0 27	70 0 -13	30 0 26	44 0 17
Moment of inertia, I_{xx}, I_{yy}, I_{zz}, slugs - in^2	5342 8613 3271	48311 236450 188130	4387 7543 2957	24218 57794 33575
Products of inertia, I_{xy}, I_{xz}, I_{yz}; slugs - in^2	0 1251 0	0 14815 0	0 1611 0	0 3939 0

The separation cutter wiring and control weight was estimated to be 5 pounds. The escape hatch pyrotechnic weights were based upon estimated weight per foot length of 0.258 lb/ft for the shape charge.

The ejection rail, catapult, power supply, controller/sensors, inertial reel/body harness weights were based upon CREST demonstration ejection seat design (Reference 2).

The recovery system weights are based upon hemisflow drogue chutes capable of opening at speeds up to Mach 4 or 2000 psf dynamic pressure. Automatic Inflation Modulation (AIM) parachutes of 36.2 feet constructed diameter were used for personal recovery parachutes for the encapsulated seats and the VLV ejection system. A cluster of three 45.5 feet constructed diameter ringslot/solid conical hybrid parachutes, similar to those being designed by Sandia for F-111 retrofit (Reference 27), were required to achieve the desired 30 ft/sec terminal velocity for the HLV pod capsule.

The encapsulated seat door weights are based upon using flexible fabric doors instead of segmented rigid metals doors. The door fabric is made from kevlar with coated urethane, is covered with Nicalon, and also has a thin ablator coating outside. It is supported by three support hoops made from aluminum.

The structural weight of the HLV pod capsule wings was estimated to be 4 pounds per square foot. The slide rail and slide blocks for the VLV pod capsule were assumed to be made from aluminum.

8.0 TRADE STUDY APPROACH

A design decision matrix approach has been used to conduct the trade studies for the best escape system concepts for the HLV and the VLV. The key features of the design decision matrix methodology are discussed in Section 8.1. The selection of the various design factors to be used in the trade study is discussed in Section 8.2. The weighting factors are discussed in Section 8.3, and the merit scales to determine the rating factors are discussed in Section 8.4

8.1 DESIGN DECISION MATRIX METHODOLOGY

A typical decision matrix is shown in Figure 8.1-1. The development of a design decision matrix consists of the following steps:

a. Selecting the important design factors to be considered for the trade study.

b. Establishing the weighting factor for each design factor.

c. Developing a merit scale for each design factor.

d. Evaluating each alternative concept to verify that minimum design requirements are satisfied. This is a necessary condition for a concept to be included on the design decision matrix. Otherwise, the linear methodology of design decision matrix may give erroneous results.

e. Evaluating each alternative concept to establish the rating factor (RF) for each design factor. These factors are determined by analysis and engineering judgment and use of the merit scale established in step c above.

f. Completing the design decision matrix (Figure 8.1-1).

For each alternative concept i, the following equations are used to calculate the total score, TS_i, for the subsystem being trade studied:

$$SS_{ij} = RF_{ij} \cdot WF_j$$
$$TS_i = \sum SS_{ij}$$

where:

j = Design factor being used for evaluation

SS_{ij} = Subscore for alternative i corresponding to design factor j

RF_{ij} = Rating factor for alternative i against design factor j

DESIGN CRITERIA / WEIGHTING FACTOR / ALTERNATIVES	PERFORMANCE CAPABILITY	WEIGHT	CREW STATION/ AIRCRAFT INTEGRATION	DEVELOPMENT RISK	SAFETY	MAINTAINABILITY	DEVELOPMENT COST	PRODUCTION COST	RELIABILITY	LOGISTICS	TOTAL SCORE
	WF_1	WF_2	WF_3	WF_4							
CONCEPT NUMBER 1	RF_{11} / SS_{11}	RF_{12} / SS_{12}									TS_1
CONCEPT NUMBER 2											TS_2
CONCEPT NUMBER 3											TS_3
CONCEPT NUMBER 4											TS_4

ABBREVIATIONS:

SS_{ij} = SUB SCORE = ($RF_i \cdot WF_j$)

RF_{ij} = Rating factor for alternative i against criteria j. The rating factor is the judged value of an alternative against a design criteria

WF_{ij} = Weighting factor for criteria j. The weighting factor is a measure of relative importance of the design criteria

TS_i = Total score for alternative i

Figure 8.1-1. A Typical Design Decision Matrix

WF_j = Weighting factor for criterion j

g. Using the total scores for the various alternative concepts to select the best one for design implementation of the subsystem being considered.

8.2 SELECTION OF DESIGN FACTORS

The following design factors were considered important in determining the best escape system concepts for the HLV and the VLV, with no implication of their relative importance by the order of their listing:

- Performance
- Weight penalty
- Crew station integration
- Vehicle integration
- Development risk
- Safety
- Reliability, maintainability, and logistics
- Development and production cost

Many of the design factors listed above need no explanation. Others are briefly discussed below.

The performance for an escape concept describes how well it meets the various performance requirements described in Section 3.1. This includes evaluation of crewmember accelerations and angular rates, low altitude performance and crossrange, as applicable.

The weight penalty of an escape concept includes only the direct increase in the vehicle weight, and not the indirect increase in the vehicle weight. The weight of the escape system and the direct increase in structural weight (such as that for backup plates in the separation areas to maintain the same load carrying capability) are thus included in the weight penalty. The indirect increase in the vehicle weight due to higher fuel requirements and the corresponding increases in structural weight are not included. The ratio of the direct and indirect increases in the vehicle weight should stay the same for the alternative concepts for any vehicle. Thus, their relative ranking on the basis of the weight penalty does not depend upon whether direct or total weight penalties are considered.

The volume considerations are included in the more general factor of crew station integration. The latter considers not only the overall volume of a concept, but also the individual dimensions and locations of the various components. It also considers the impact on crew ingress/egress, mobility, vision and comfort.

8.3 WEIGHTING FACTORS

The weighting factors used for the various design factors in the escape concept trade studies are shown in Table 8.3-1. The relative values of the weighting factors correspond directly to the relative importance of the various design factors, with the more important design factors assigned the higher values. Thus, the weight penalty due to the escape concepts is assigned the highest weighting factor of 10, while the logistics was assigned a relatively low weighting factor of only 2.

The assignment of weighting factors for any trade study is subjective. In order to minimize personal biases, opinions of various team members supporting the escape concept trade study were sought, and a consensus reached.

In any case, the effect of choosing a different set of weighting factors on the best escape concept selection can be easily evaluated from the basic rating factor data presented in this report.

8.4 MERIT SCALES AND RATING FACTORS

Merit scales are used to determine the rating factors for each design alternative so that a design decision matrix (such as that shown in Figure 8.1-1) can be completed, and the best alternative selected. It should be noted that in establishing such merit scales:

a. Only the alternatives that meet the minimum design requirements, are evaluated on the basis of the design decision matrix. If a concept does not meet the minimum specified requirements, it is excluded from further evaluation (with the rationale documented). Such an exclusion is necessary to make the linear combination methodology of the design decision matrix a viable design tool.

b. Good judgment has to be used in selecting the merit scale curve, so that it covers the whole range of the evaluated design factor, as well as has good fidelity in the expected range of the design factor.

The merit scales were selected so that the alternative concepts were given a rating factor from 0 to 10, with the best possible system getting a score of 10 and the worst system (which is barely acceptable) a score of 0.

Table 8.3-1. Weighting Factors

Design factors	Weighting factor	
	Relative	Normalized
Performance	8	0.16
Weight penalty	10	0.20
Crew station integration	5	0.10
Vehicle integration	5	0.10
Development risk	4	0.08
Safety	5	0.10
Reliability	5	0.10
Maintainability	2	0.04
Development cost	2	0.04
Production cost	2	0.04
Logistics	2	0.04
		1.00

There were two basic ways in which the goodness of a concept with respect to a specific design factor was given a rating factor.

If the merit of the concept could be evaluated on the basis of a single parameter value (such as weight penalty or cost), the merit scale was a curve relating this parameter to the rating factor. On the other hand, if qualitative judgement was necessary to evaluate the merit of a concept, then the scoring system shown in Table 8.4-1, or a slight variation thereof, was used.

The merit scales used for various design factors are discussed in the following subsections.

8.4.1 Merit Scales for Performance

The performance variables used for conducting capsule performance correspond to the performance requirements discussed in Section 3.1. These are: acceleration and angular rates experienced by the crewmembers, minimum altitude required for survival, distance away from explosion and crossrange, as applicable. The merit scale for each of these performance variables is discussed in the following paragraphs. The requirements on maximum long-term acceleration, long-term angular rate, structural temperature, pressure, oxygen, carbon dioxide, environmental temperature, windblast protection, and ionizing radiation were satisfied by design and were not specifically included in the trade study.

8.4.1.1 Merit Scale for Acceleration Radical

The merit scale used for acceleration radical is shown in Figure 8.4-1. For the purpose of using this merit scale, acceleration radical for all flight conditions were calculated by using the limits for high risk. An acceleration radical response with a maximum amplitude anywhere below 0.3 was considered to meet the objective of minimizing the radical as much as necessary to avoid injuries and received a score of 10.0. Then the score was decreased linearly until the radical limit value of 1.0 was reached.

8.4.1.2 Merit Scale for Altitude Required for Survival

The merit scale used for the minimum altitude (above ground) required for survival is shown in Figure 8.4-2. The actual altitude lost between escape initiation and reaching the design terminal velocity for any flight condition is compared with the corresponding altitude requirement in Table 3.1-2, and used to calculate the rating factor score.

Table 8.4-1. Merit Scale Relating Qualitative Assessment to Rating Factor

Assessment	Qualitative rating	Rating factor
Barely meets the absolute requirement	Barely acceptable	0.0
Much less than the established objectives	Poor	2.0
Less than the established objectives	Fair	4.0
Meets objectives	Good	6.0
Somewhat better than meeting objectives	Very good	8.0
Much better than meeting objectives	Excellent	10.0

Note: A rating factor value in between those listed above may be assigned.

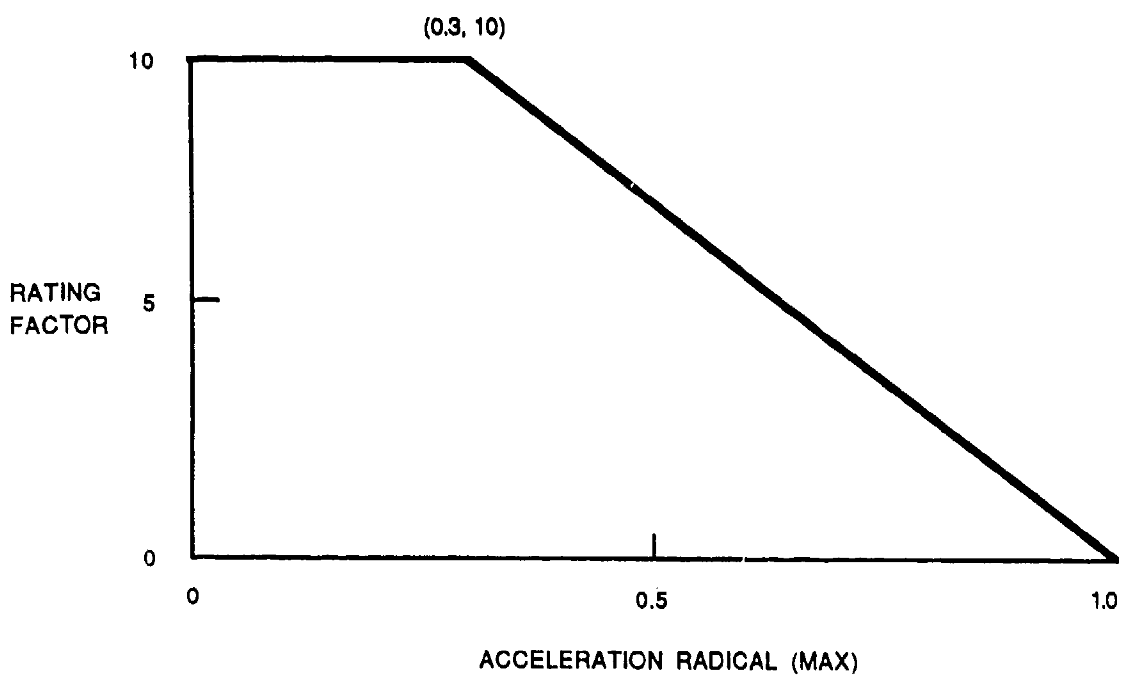


Figure 8.4-1 Merit Scale for Acceleration Radical

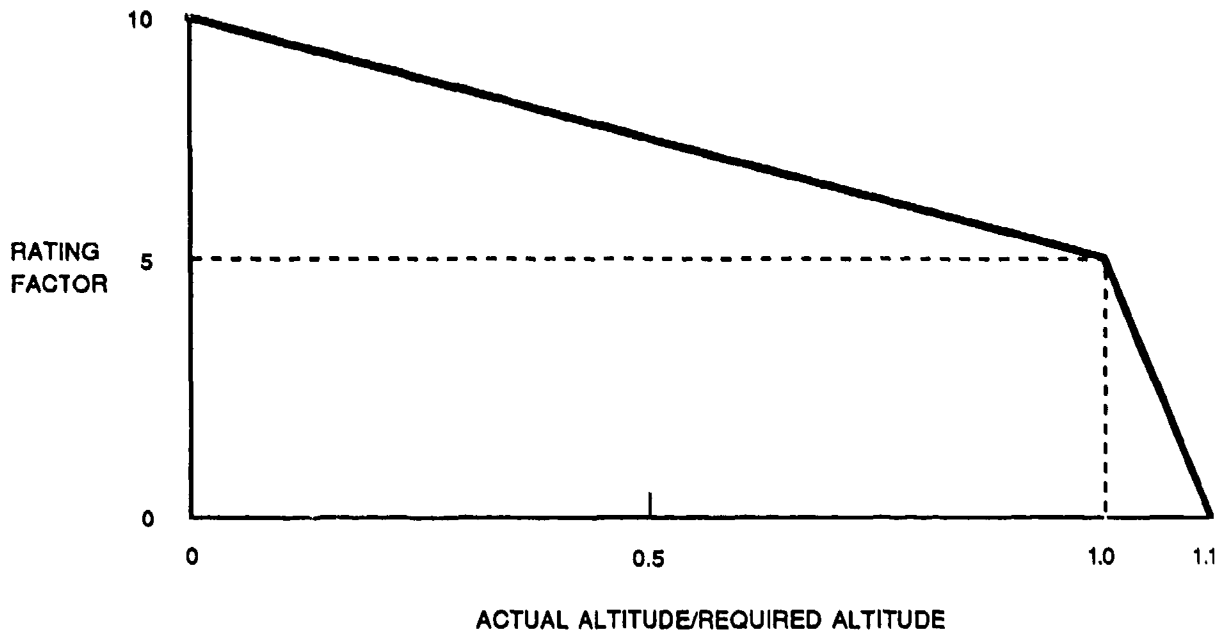


Figure 8.4-2. Merit Scale for Altitude Required for Survival

Overshoots of up to 10 percent in allowed altitude are accepted under the assumption that minor modifications in escape concept design will correct the overshoot.

8.4.1.3 Merit Scale for Attitude Rates

This criterion addresses the maximum attitude rates experienced for each escape concept in each of the three axes. Merit was assigned based on the magnitudes of the maximum attitude rates relative to the specified Short Duration Attitude Rate Limits (Appendix A). These limits are different for each axis and vary with risk level.

For a given flight condition, the absolute value of the maximum amplitude in each axis was first normalized by the appropriate limit. Then the average of the three axes' normalized values was calculated. The score was based on this averaged normalized value. Since the objective was to minimize the attitude rates, the linear merit scale shown in Figure 8.4-3 was appropriate.

8.4.1.4 Merit Scale for Distance Away From Explosion

All the four HVT escape system concepts enclose the crewmembers completely. Thus, protected tolerance curves shown in Figure 3.1-2 can be used to ensure crewmember safety. Also, the protection provided by the alternative concepts can be treated on an equal basis by considering the distance away from the explosion at a fixed time to rate the various concepts. Figure 8.4-4 shows the merit scale used for distance away from explosion. The time selected for this distance was 5 seconds.

8.4.1.5 Merit Scale for Crossrange Distance

An extended crossrange capability for escape initiated during upper atmospheric hypervelocity flight is a very desirable feature to have. The merit scale shown in Figure 8.4-5 was found to be appropriate for relative rating of the alternative escape system concepts.

8.4.1.6 Merit Scale for Sustained Acceleration

The linear acceleration limits are, in general, a function of time for which high acceleration levels are sustained. During dynamic simulations for descent from orbit, maximum acceleration levels were maintained only for a minute or less, when the escape vehicle encountered maximum dynamic pressure. Linear acceleration limits at 1 minute, as shown in Figure 3.2-1, were therefore considered to be the maximum acceptable and given a score of 0. The maximum value of 10 was assigned to zero acceleration level, as shown in Figure 8.4-6.

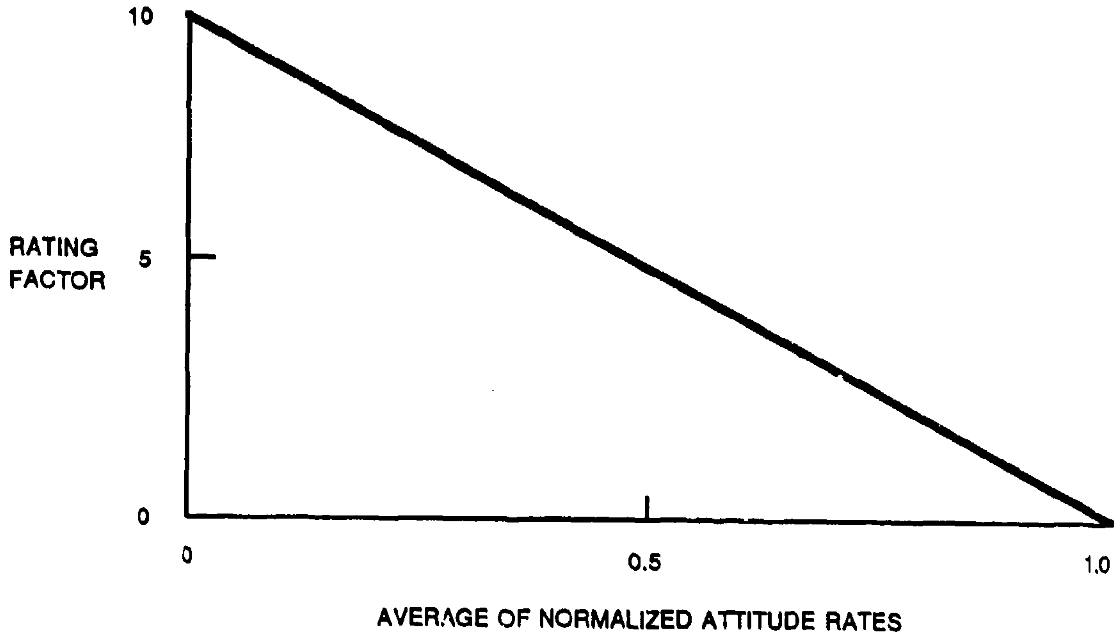


Figure 8.4-3. Merit Scale for Attitude Rates

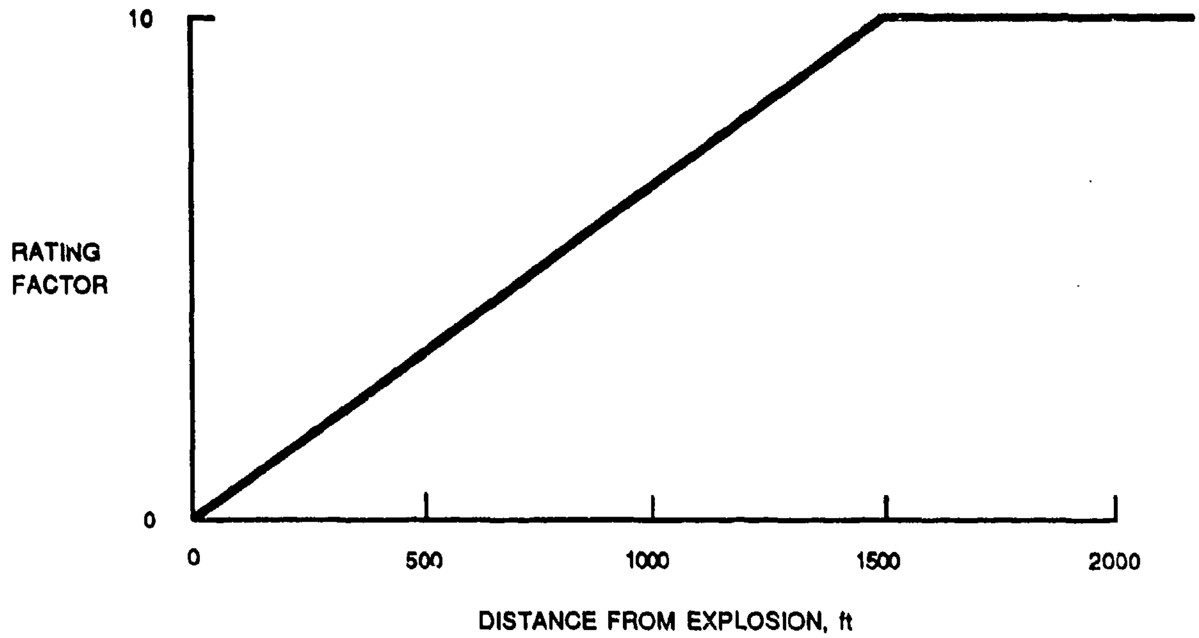


Figure 8.4-4. Merit Scale for Distance Away from Explosion

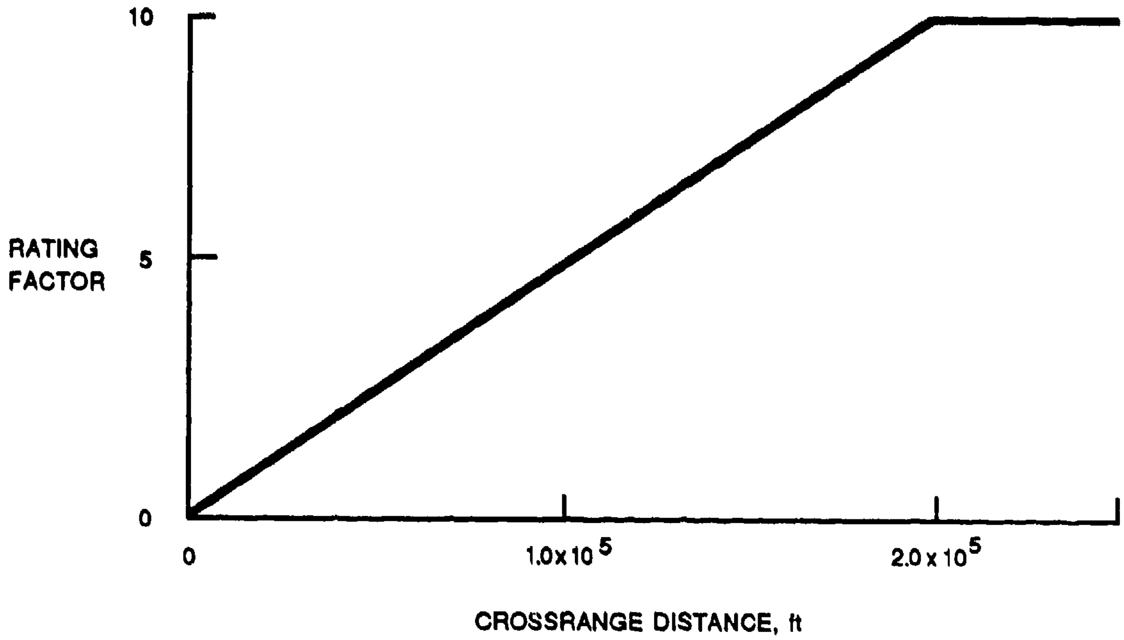


Figure 8.4-5. Merit Scale for Crossrange

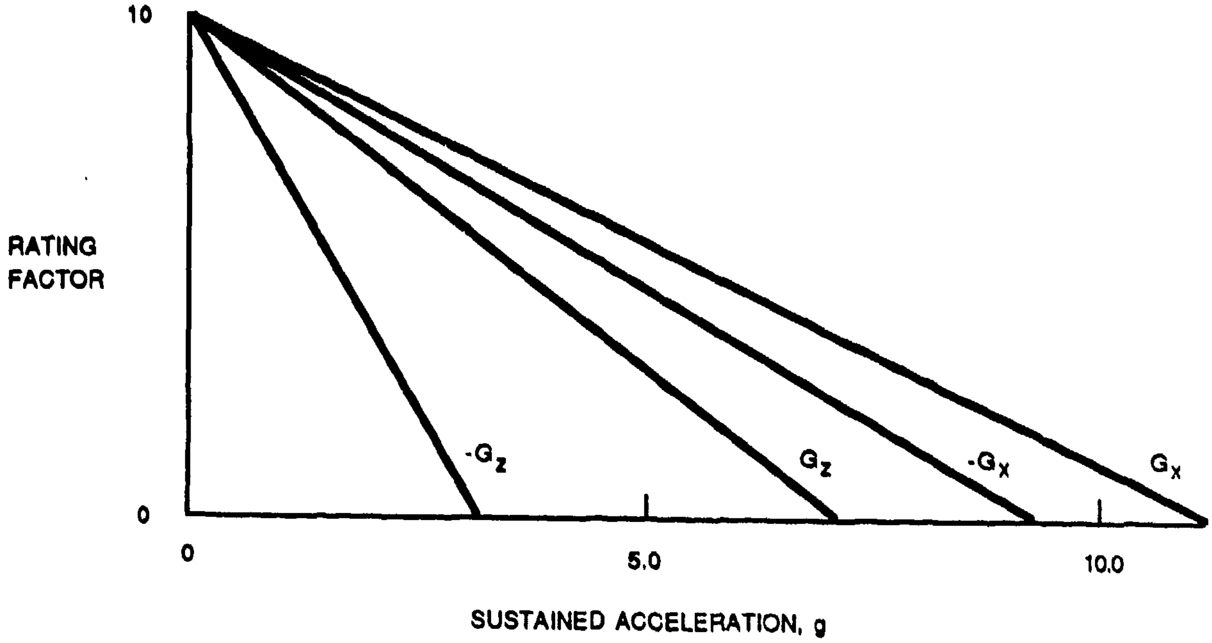


Figure 8.4-6. Merit Scale for Sustained Acceleration

8.4.1.7 Composite Score for Performance Factors

The composite score for performance factors was taken as the average of the applicable performance factors, such as acceleration radical or minimum altitude required for survival.

8.4.1.8 Composite Score for Flight Conditions

The overall performance score for any escape concept was taken as the average of the performance scores for the individual flight conditions.

8.4.2 Merit Scale for Weight Penalty

The merit scale used for rating the direct weight penalty of various crew escape concepts is shown in Figure 8.4-7. The same scale was applied to both the HLV and the VLV escape concepts by using the weight penalty goal as a normalizing factor.

The selected values for the weight penalty goals were 1250 pounds and 750 pounds for the HLV and the VLV escape concepts respectively. These goals were selected so that the weight penalties for all the concepts were within 80 to 200 percent of the established goals.

8.4.3 Merit Scale for Crew Station Integration

The various crew station integration factors were evaluated qualitatively using the merit scale shown in Table 8.4-1. These factors included impact on:

- Transparency Design
- Pilot Ingress/Egress
- Restraint System
- External Vision
- Seat Recline Angle
- Controls and Displays Reach
- Primary Controls Reach
- Heads-Up Display (HUD)
- Displays/Internal Vision

8.4.4 Merit Scale for Vehicle Integration

The various vehicle integration factors were also evaluated qualitatively using the merit scale shown in Table 8.4-1. These factors included:

- Ease of locating escape system components

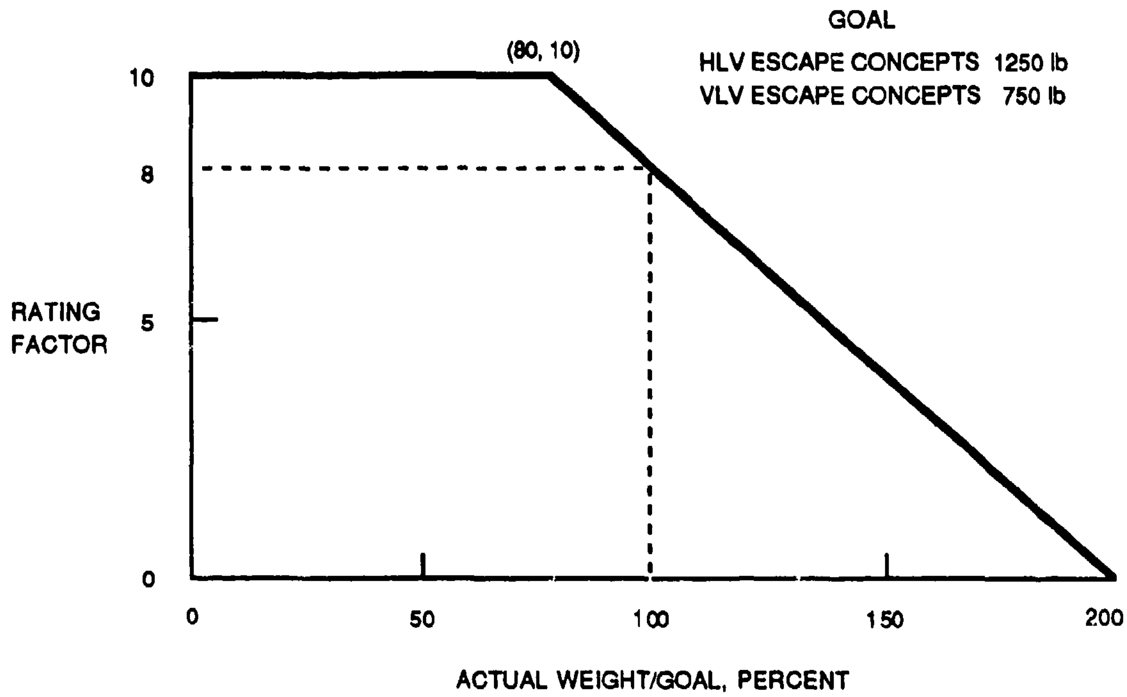


Figure 8.4-7. Merit Scale for Weight Penalty

- Impact on vehicle component location
- Ease of vehicle/escape system separation components design.

8.4.5 Merit Scale for Development Risk

The following guidelines were used for the qualitative assessment of hardware development risk:

Off-the-shelf, unmodified	no risk
Off-the-shelf, minor modifications	low risk
Operational test on similar hardware complete	low risk
Qualification test on similar hardware complete	low risk
Design development complete, minor advance in technology	low to medium risk
Engineering development complete, major jump in technology	medium to high risk
Conceptual only, major jump in technology	high to very high risk

The merit scale of Table 8.4-2 was then used to relate this qualitative assessment to a rating factor.

8.4.6 Merit Scale for Safety

System safety evaluation was qualitative, based on experience with similar systems. Both the severity and the probability of occurrence of various safety hazards was considered. The merit scale of Table 8.4-1 was then used to calculate the corresponding rating factors.

8.4.7 Merit Scale for Reliability

The expected reliability of different crew escape concepts was also evaluated qualitatively, and then assigned appropriate rating factors by using the merit scale of Table 8.4-1.

8.4.8 Merit Scale for Maintainability

The accessibility and complexity of each of the escape concept subsystems were evaluated qualitatively using the merit scale of Table 8.4-1. These were then averaged to determine the corresponding rating factors for maintainability.

Table 8.4-2. Merit Scale for Development Risk

Assessment	Rating factor
Extremely high risk	0.0
High risk	2.5
Medium risk	5.0
Low risk	7.5
No risk	10.0

8.4.9 Merit Scale for Development Cost

The merit scale for cost shown in Figure 8.4-8 was used for determining the rating factor for development cost. The escape concepts were considered as high cost items for using this scale.

8.4.10 Merit Scale for Production Cost

The merit scale used for production cost also corresponded to the high cost item line in Figure 8.4-8.

8.4.11 Logistics

The following logistics factors were evaluated qualitatively using the merit scale of Table 8.4-1:

- Maintenance skill requirements
- Maintenance personnel requirements
- Support equipment
- Special maintenance tools
- Spares

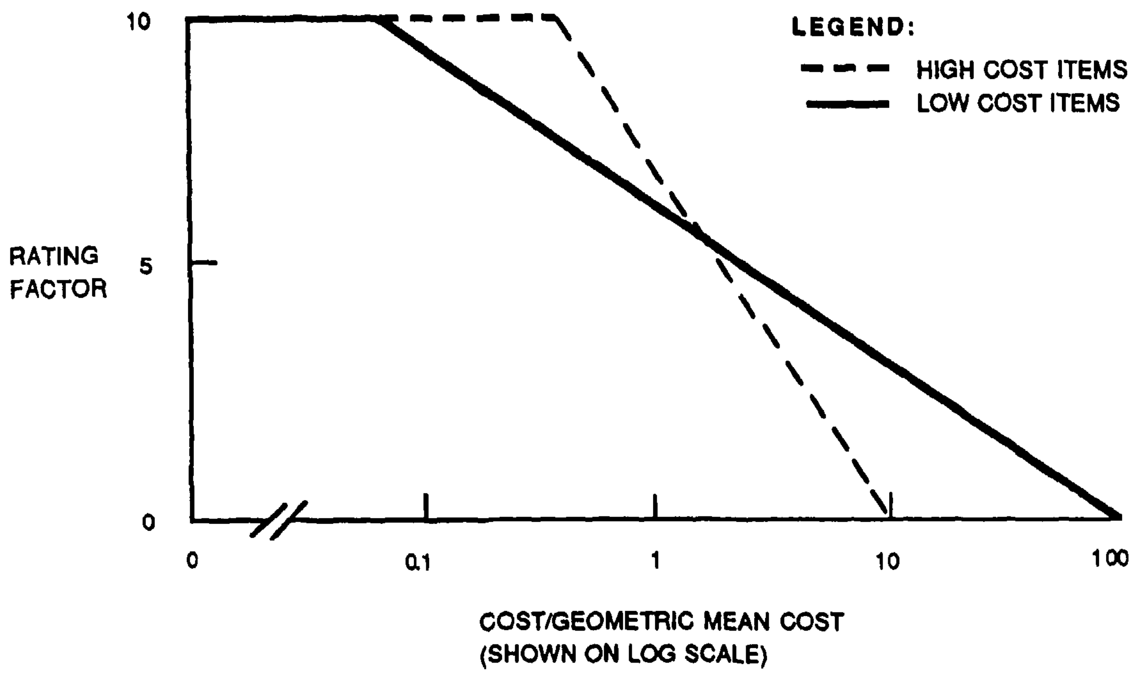


Figure 8.4-8. Merit Scale for Cost

9.0 TRADE STUDY RESULTS

The evaluation of the various HVT escape system concept on the basis of the established design criteria is discussed in the following subsections. The trade study results are summarized in Table 9.0-1. It may be noted that on the basis of the established design criteria, the encapsulated seats were overall superior to the pod capsules for HLV as well as VLV.

9.1 PERFORMANCE

The performance of the various HVT escape system concepts was evaluated on the basis of dynamic simulation results for the escape conditions shown in Table 9.1-1. The dynamic simulations were conducted using EASY5 program (Reference 23). As examples, dynamic simulation results for a single-place encapsulated seat are shown in Appendix B for escape conditions 3 and 4 of Table 9.1-1.

The aerodynamic coefficients used for different escape concepts were as shown in Figures 7.1-2 through 7.1-16. The propulsion subsystem thrust and impulse levels were as given in Table 7.3-1. The weight and inertial properties of the escape concepts were as listed in Table 7.5-5. The control law was essentialy the same as that used for ejection seats on the CREST program (Reference 2) and for capsules on the ACECT program (Reference 1), although some adjustment of control low gains was required.

The dynamic analysis for the orbital escape condition, condition 4, was made significantly simpler than other conditions to avoid excessively high computation times. Firstly, it was assumed that the escape system maintains the desired angle of attack (15 degrees in analysis) during reentry into atmosphere, so that the relatively fast dynamics of the controller and the propulsion system did not have to be simulated. Secondly, the spin velocity of the earth was neglected, which allowed use of a more efficient simulation model. This approach did not have appreciable effects on the parameters of interest, such as altitude, Mach no., acceleration or heating rate time histories, and thus did not affect the trade study results for the various concepts.

The dynamic simulations for the dual-place encapsulated seat and the HLV pod capsule assumed two 99 percentile crewmembers, since this resulted in maximum propulsion system thrust and impulse requirements. The capability to control the escape concepts adequately with crewmembers with widely varying characteristics, such as fifth and ninety-fifth percentile crewmembers, was provided by designing roll/yaw reaction jet propulsion system of sufficient thrust and impulse (see Section 7.3.3).

Table 9.0-1. Design Decision Matrix For HVT Crew Escape Concepts

Design factors		Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Description	Weighting factor				
Performance	0.16	7.5	8.0	7.3	8.3
Weight penalty	0.20	9.1	0.6	8.5	0.9
Crew station integration	0.10	5.3	7.1	6.0	7.4
Vehicle integration	0.10	5.7	6.2	6.3	6.5
Development risk	0.08	5.8	6.1	6.2	7.0
Safety	0.10	5.6	5.0	6.0	5.4
Reliability	0.10	6.5	5.0	7.0	5.5
Maintainability	0.04	7.1	5.9	7.4	7.3
Development cost	0.04	6.0	4.3	7.5	6.1
Production cost	0.04	6.3	4.3	7.4	5.9
Logistics	0.04	7.4	5.8	7.8	6.4
Total score		6.86	5.03	7.11	5.58

Table 9.1-1. Escape Conditions for Performance Analysis

No.	Altitude, ft.	Speed, ft/sec	Pitch angle, deg	Roll angle, deg	Sideslip angle, deg	Flight path angle, deg
1	Low	0	0	0	0	0
2*	Low	0	90	0	0	90
3	Low	422	-10	180	0	-10
4	300,000	25,332	0	0	0	0
5	175,000	15,000	0	0	0	0

* Vertically-launched vehicle only

The performance results and the corresponding rating factors for the various escape conditions are summarized in Tables 9.1-2 through 9.1-11. The rating factors were derived from the performance results using the merit scales for acceleration radical, required altitude, attitude rates, distance from explosion, crossrange distance, and sustained acceleration shown in Figures 8.4-1 through 8.4-6. The composite rating factors for performance were derived by averaging the rating factors for individual escape conditions, as shown in Table 9.1-12. The pod capsules had, on the whole, better performance than the encapsulated seats.

9.2 WEIGHT PENALTY

The weight penalties and the corresponding rating factors for the four crew escape concepts are shown in Table 9.2-1. Each weight penalty is the direct weight impact of the corresponding crew escape system on the corresponding hypervelocity vehicle, compared to the vehicle without an escape system. The rating factors were derived from the weight penalties using the merit scale in Figure 8.4-7.

The structural weight penalty of the dual-place encapsulated seat is its total structural weight of 220 pounds (Table 7.5-1) minus the weight of two nonejectable seats, each of which is assumed to weigh 60 pounds. Similarly, the structural weight penalty of the single-place encapsulated seat is its total structural weight of 120 pounds minus 60 pounds weight of a nonejectable seat. The structural weight penalties for HLV pod capsule and the VLV pod capsule are due to localized increase in structural thickness to withstand additional propulsive forces.

The instruments, ECS, and avionics add to the ejected weight but not to the weight penalty of any escape concepts. The weight penalties of the separation system, escape hatch pyrotechnics, life support system, main propulsion system, attitude control system, recovery system, heat shield, power supply, survival kit, controllers/sensors, ejection rail, catapult, door, wings with actuation system, flotation system, extraction system, and slide blocks (as applicable) are the same as the corresponding weights shown in Table 7.5-1. The inertia reel and body harness weights reflect the increase in weight due to parachute harness and the improved haulback system required to position the crewmember properly before the seat or capsule ejection.

9.3 CREW STATION INTEGRATION

The rating factors for crew station integration were assigned by a qualitative assessment of the various crew station integration factors using the merit scale shown in

Table 9.1-2. Performance Results for Condition 1

Performance variable	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Acceleration radical	0.49	0.47	0.48	0.48
Altitude required, ft	0	0	0	0
Maximum angular rates in roll, pitch and yaw, deg/sec	52, -330, -46	30, 28, 17	56, -290, -48	56, -290, 16
Distance away from explosion, ft	598	711	426	1250
Crossrange, ft	-	-	-	-

Table 9.1-3. Performance Rating Factors for Condition 1

Performance variable	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Acceleration radical	7.3	7.6	7.4	7.4
Altitude required, ft	10.0	10.0	10.0	10.0
Maximum angular rates in roll, pitch and yaw, deg/sec	8.9	9.8	9.0	9.1
Distance away from explosion, ft	4.0	4.7	2.8	8.3
Crossrange, ft	--	-	-	-
Average	7.6	8.0	7.3	8.7

Table 9.1-4. Performance Results for Condition 2

Configuration	*Dual-place encapsulated seat	*HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Acceleration radical	-	-	0.47	0.23
Altitude required, ft	-	-	0	0
Maximum angular rates in roll, pitch and yaw, deg/sec	-	-	0, -7, 0	0, -5, 0
Distance away from explosion, ft	-	-	957	378

*Condition 2 is not applicable to these configurations.

Table 9.1-5. Performance Rating Factors for Condition 2

Performance variable	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Acceleration radical	Not applicable	Not applicable	7.6	10.0
Altitude required, ft	Not applicable	Not applicable	10.0	10.0
Maximum angular rates in roll, pitch and yaw, deg/sec	Not applicable	Not applicable	10.0	10.0
Distance away from explosion, ft	Not applicable	Not applicable	6.4	2.5
Crossrange, ft	Not applicable	Not applicable	-	-
Average	Not applicable	Not applicable	8.5	8.1

Table 9.1-6. Performance Results for Condition 3

Configuration	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Acceleration radical	0.43	0.50	0.54	0.42
Altitude required, ft	210*	125	183*	108
Maximum angular rates in roll, pitch and yaw, deg/sec	-344, 123, -63	-264, 129, -50	-360, 120, -63	-320, 112, -54

*Dependent upon parachute design.

Table 9.1-7. Performance Rating Factors for Condition 3

Performance variable	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Acceleration radical	8.1	7.1	6.6	8.3
Altitude required, ft	8.3	9.0	8.5	9.1
Maximum angular rates in roll, pitch and yaw, deg/sec	8.7	8.9	8.7	8.8
Distance away from explosion, ft	-	-	-	-
Crossrange, ft	-	-	-	-
Average	8.4	8.4	7.9	8.7

Table 9.1-8. Performance Results for Condition 4

Configuration	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Sustained acceleration, G_X	-1.00	-2.05	-.094	-1.96
Sustained acceleration, G_Z	0.43	1.44	0.39	1.24

Table 9.1-9. Performance Rating Factors for Condition 4

Configuration	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Sustained acceleration, G_X	8.9	7.7	9.0	7.8
Sustained acceleration, G_Z	9.5	8.4	9.6	8.6
Average	9.2	8.1	9.3	8.2

Table 9.1-10. Performance Results for Condition 5

Configuration	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Acceleration radical	0.77	0.36	0.81	0.46
Altitude required, ft	-	-	-	-
Maximum angular rates in roll, pitch and y~w, deg/sec	160, 120, -6	123, -22, 8	160, 120, -8	64, 9, 2
Distance away from explosion, ft	-	-	-	-
Crossrange, ft	0.23×10^5	0.82×10^5	0.24×10^5	1.29×10^5

Table 9.1-11. Performance Rating Factors for Condition 5

Performance variable	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Acceleration radical	3.3	9.1	2.7	6.6
Altitude required, ft	-	-	-	-
Maximum angular rates in roll, pitch and yaw, deg/sec	9.3	9.6	9.3	9.8
Distance away from explosion, ft	-	-	-	-
Crossrange, ft	1.2	4.1	1.2	6.5
Average	4.6	7.6	4.4	7.6

Table 9.1-12. Rating Factors for Performance

Condition	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
1	7.6	8.0	7.3	8.7
2	-	-	8.5	8.1
3	8.4	8.4	7.9	8.7
4	9.2	8.1	9.3	8.2
5	4.6	7.6	4.4	7.6
Average	7.5	8.0	7.3	8.3

Table 9.2-1. Weight Penalty and Rating Factor

Subsystems	Dual-place encapsulated seat (lb)	HLV pod capsule (lb)	Single-place encapsulated seat (lb)	VLV pod capsule (lb)
Structure (not including seat weight)	100	50*	60	40
Instruments, ECS, Avionics	-	-	-	-
Separation system	5	22	5	16
Escape hatch pyrotechnics system	5	4	4	4
Life support system	43	43	28	28
Main propulsion system	228	724	131	316
Attitude control system	137	219	110	183
Recovery system	53	167	28	-
Heat shield	260	877	170	610
Power supply	20	20	10	20
Survival kit	60	60	30	30
Controller/sensors	21	25	21	25
Ejection rail	50	-	36	50
Catapult	68	-	51	-
Door	62	-	40	-
Inertial reel body harness	20	10	10	5
Wings with actuation system	-	118	-	-
Flotation system	-	67	-	-
Extraction system	-	-	-	60
Slide blocks	-	-	-	30
Weight penalty, total	1132	2406	734	1417
Rating factor	9.1	0.6	8.5	0.9

Table 8.4-1. These rating factor values are shown in Table 9.3-1. The rationale for these values is provided in the following paragraphs.

9.3.1 Impact On Transparency Design

Due to high heating loads associated with the hypersonic flights, the transparency areas for both HLV and VLV are small. For the HLV, there are only two side windows: there is no windshield. For the VLV, there is a windshield as well as two side windows. However, for none of the two vehicles, the hatches required for the encapsulated seats or the extraction system affect the design of the transparencies. There is no other impact of pod capsules or encapsulated seats on transparencies. All the concepts are therefore, given a score of 10.

9.3.2 Pilot Ingress/Egress

There is no impact of pod capsules on the normal pilot ingress/egress. For emergency egress after landing, the access door in the HLV floor may not be available due to the floor resting on the ground. Thus, a hatch to exit the capsule from the top is required. There is no such problem on the VLV, where a hatch is provided for the extraction system to pull the crewmember out of the cockpit.

Due to their larger size, the encapsulated seats make the pilot ingress/egress harder. Also, for the HLV, the pilots' access to the seat requires either a hatch through the heat-shield or a complete change of access to the cabin. If an HLV pod capsule is used, then the pilots enter the cabin through the existing access door in the floor aft of the seats.

9.3.3 Impact On Restraint System

All the escape concepts protect the crewmembers against windblast and thus no leg or arm restraints are required to protect against limb flailing at high speeds. The HLV pod capsule provides more flexibility in lateral restraint design and also does not require a parachute harness.

9.3.4 External Vision

External vision is better with the nonejectable seats of the pod capsules than with the encapsulated seats. Even with the pod capsule, the external vision is only poor to fair with the HLV.

Table 9.3-1. Rating Factors For Crew Station Integration

Design factors	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Impact on transparency design	10.0	10.0	10.0	10.0
Pilot ingress/egress	5.0	7.0	8.0	9.0
Impact on restraint system	6.0	8.0	6.0	6.0
External vision	2.0	3.0	5.0	6.0
Seat reclination capability	2.0	2.0	2.0	2.0
Controls and displays reach	5.0	8.0	5.0	8.0
Primary controls	6.0	8.0	6.0	8.0
Impact on head-up displays	6.0	9.0	6.0	9.0
Displays/internal vision	6.0	9.0	6.0	9.0
Average	5.3	7.1	6.0	7.4

9.3.5 Seat Reclination Capability

Neither the encapsulated seats nor the pod capsules lend themselves to anything other than a very nominal degree of seat reclination - nothing approaching the ›5 to 60 degree required to significantly affect "G" tolerance.

9.3.6 Controls And Displays Reach

The flat panel displays allow touch panel overlays on bezel switches. If encapsulated seats are used, these flat panels must be located outside the space required for ejection and can be accessed by the smaller pilot only when his harness is unlocked.

The enormous potential of the multifunction display (MFD) is thus relegated to zone 3 control function. If pod capsules are used, then zone 1 MFD control of the aircraft is possible; i.e., these controls and displays become accessible with the shoulder harness locked and shoulders against the seatback.

9.3.7 Primary Controls

Fly-by-wire flight control allows location of primary controls within the encapsulated seat for emergency operation during cabin depressurization with only a small increase in complexity. The pod capsules do allow more flexibility in location of the primary control.

9.3.8 Impact on Head Up Displays (HUD)

A large HUD total field of view (TFOV) is desirable. Eliminating the ejection envelope associated with encapsulated seats allows the combiner and attendant project equipment to be moved closer to the design eye point (DEP), thus increasing TFOV.

9.3.9 Displays/Internal Vision

Enough front panel display area is a critical consideration. Use of pod capsules instead of encapsulated seats allows the panels to be moved closer to the pilots, thus providing larger field of view.

9.4 VEHICLE INTEGRATION

Three factors were considered for the vehicle integration assessment:

- o Ease of escape system component location, which includes the space available compared with the number and sizes of the necessary components and the required number of subsystems interfaces;

- Impact on vehicle component location, which includes the number of non-escape system vehicle components that need to be relocated and the expected complexity of doing so; and
- Separation component design, which includes the number and design complexity of the structural and other components that must be physically separated during the escape sequence.

The above vehicle integration factors were rated using the merit scale given in Table 8.4-1. The corresponding scores are given in Table 9.4-1. The rationale for this assessment is provided below.

Escape System Component Location. Because of their lower ejected weights, both encapsulated seat designs have smaller propulsion, recovery, and other subsystem components than either pod capsule. However, all the components must be carried in the seat which cannot be too large since it has to fit into the space normally occupied by a conventional seat, its occupant and part of the side control panels. While the available space is small, current completed studies indicate that there is adequate volume in the single-place seat and much more space available in the dual-place seat, especially if a capsule aft entry hatch providing access between the seat is not required.

The two seats require primary control output and electrical interfaces. These include control stick, throttle, escape system/vehicle computer data interface, electrical power connections, life support system connections, and probably keyboard.

The vertically launched vehicle (VLV) pod capsule configuration has a lot of space for escape system components since the cabin was originally designed for a two-man crew, and, also because a large amount of volume is available between the cabin floor and the vehicle propellant tanks.

The required VLV/capsule subsystem interfaces include airframe controls (landing gear, aerodynamic surfaces, auxiliary power, etc.), engine controls, electrical power, avionics interfaces, and environmental control system connections.

For the horizontally launched vehicle (HLV) pod capsule, many of the escape system components, including the propellant tanks and life support system, are in the constrained space under the cabin floor. The heat shield, main thrusters, and recovery systems are outside the cabin, where there is much more room because the long, conical forebody required for aerodynamic considerations is only partially filled by cooling system, attitude control thrusters, cabin, and nose landing gear. The in-cabin placement problem, however, makes this concept the most difficult one from the component location standpoint.

Table 9.4-1. Rating Factors for Vehicle Integration

Evaluation factors	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Escape component location				
1. Available component space	8.0	4.0	6.0	9.0
2. Number of interfaces	6.0	7.0	6.0	5.0
Average score	7.0	5.5	6.0	7.0
Vehicle component location impact				
1. Number of changes	4.0	8.0	6.0	7.0
2. Complexity	6.0	10.0	8.0	9.0
Average score	5.0	9.0	7.0	8.0
Separation component design				
1. Number of components	6.0	6.0	6.0	5.0
2. Complexity	4.0	2.0	6.0	4.0
Average score	5.0	4.0	6.0	4.5
Overall average score	5.7	6.2	6.3	6.5

Aside from the structural connections, the airframe and engine controls mentioned earlier for the VLV pod electrical power, and the cooling system would be connected between the pod and the rest of the vehicle.

Vehicle Component Location Impact. This factor describes the number and complexity of the non-escape system component relocations required by the concept either for system operation or to reduce capsule ejected weight.

For both encapsulated seats the primary controls are relocated into the seat for vehicle control from within the sealed capsule. This would be done in the event of a cabin atmosphere contamination or depressurization. Cockpit side panels would have to be moved outward from the seat centerlines from the usual 10 inches to 18 inches to accommodate the seat shell structure, the floor would be removed under the crew station for the same reason. In addition, the egress hatch would be moved from the aft floor to the ceiling over the crew station for the dual-place seat if the aft hatch approach is not used. This would be a complicating factor since the new hatch would no longer be protected from aerodynamic heating and loading by the nose wheel doors, and a relatively simple plug type hatch would have to be replaced with an outward opening, heat-shielded door.

The only change identified for the VLV pod, in which most of the ECS and avionics systems are already located outside of the cabin, is to reconfigure the floor to provide space for the propulsion system.

As currently arranged, few, if any, vehicle components would need to be relocated for the HLV pod design, although it may be necessary to reconfigure the equipment bays to move the center of gravity location to improve the system's aerodynamic stability. A major disadvantage of this configuration is the inclusion of the pressurized equipment bay in the escape capsule which greatly increases the capsule's ejected weight along with the sizes of the heat shield, propulsion, recovery, and impact attenuation systems. Elimination of this problem would involve a major concept reconfiguration that would include a pressurized equipment bay separate from the cabin. The evaluated HLV pod capsule configuration, however, does not include this major change.

Separation Component Design. The encapsulated seats would require catapults and rails similar to those used on current ejection seats along with a more complex aircraft services connector similar to that being developed under the CREST program. Ejection panels or hatches would also be required and could be similar to those used on the first four space shuttle development flights. Panel construction on the HLV dual seat design would be expected to be more complex due to the much higher aerodynamic forces and heating loads it would encounter.

The VLV pod would use large blowaway panels similar in construction to, but more complex than, the ejection panels mentioned earlier. ECS and avionics system interfaces would be severed by relatively simple linear shaped charge cutter assemblies, while the separation guide rails would be minor modifications to already existing structure with structurally uncomplicated slipper blocks.

The HLV pod has no rails or slipper block system, and the number of vehicle interfaces to be severed by the cutter assemblies would be less. The blowaway panels in this concept are much larger, however, and will probably require a rocket jettison system as well as increased structure to support the forebody loads during separation.

9.5 DEVELOPMENT RISK

The development risk rating factors for the four crew escape concepts were determined using the guidelines in Section 8.4.5 and the merit scale in Table 8.4-2. These rating factors are summarized in Table 9.5-1. The rationale for these scores is discussed in the following paragraphs.

The digital controllers and most of the sensors for all four configurations are modifications of those being developed and tested on the CREST program. The additional sensor to determine position w.r.t. points on earth is also under development, as discussed in Section 6.7. Design development is, therefore, considered to have only a low to medium risk.

The single place encapsulated seat would have a recovery system similar to current ejection seats and the VLV pod uses an F-111 type drogue and a T-28 type extraction rocket for low risk due to past operational tests on similar hardware. The dual-place seat carries a higher risk due to the two parachutes and the separation of two crew members from the seat. The parachute with retrorocket landing system, used on the HLV pod capsule, has undergone development testing on the B-1A and Gemini programs and has been in operation on the Soviet Soyuz manned spacecraft for 20 years. Developing a system of this type is considered a low to moderate risk.

All four concepts use advanced gelled propulsion/attitude control systems. This major technology has been under development for several years but has not yet been put into use. It is, therefore, considered a medium to high development risk. Addition of a catapult, essentially a modified off-the-shelf design, for the encapsulated seats would increase the risk slightly.

The four survival kit installations are essentially off-the-shelf hardware with no development risk.

Table 9.5-1. Rating Factors for Development Risk

Subsystems	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Controller/sensors	6.5	6.5	6.5	6.5
Recovery	6.5	6.5	7.5	7.5
Propulsion	3.5	4.0	3.5	4.0
Survival kit	10.0	10.0	10.0	10.0
Structure	1.0	3.0	1.0	7.5
Life support	7.5	7.5	7.5	7.5
Separation	6.0	6.0	7.5	7.5
Heat shielding	6.2	6.2	6.2	6.2
Restraint	5.0	5.0	6.0	6.0
Concept average	5.8	6.1	6.2	7.0

Although it is based on materials and concepts that have already undergone development testing for aerobraking ballutes, the encapsulated seat doors made of fabric are still in the conceptual stage and are considered an extremely high risk. A fallback position of a rigid, B-58 seat type door provides a lower risk but heavier and bulkier alternative. The VLV pod structure is similar in concept and technology to the F-111 and B-1A crew modules and is considered a low development risk. The HLV pod is similar in concept, but use of new exotic materials and structural concepts requires a major jump in structures technology with a medium to high risk.

All escape concepts use open life support systems similar to those used on current, high altitude aircraft. Use of these operationally tested technologies results in low risk for the systems.

The single-place encapsulated seat uses an ejection hatch similar to those used on the shuttle development flights and would carry a low development risk. The dual-place version uses a similar arrangement, but the structural innovations required for use on the HLV introduce some unknowns, increasing the risk. The VLV pod separation system uses linear shaped charges to severe blowaway panels and is similar to concepts used on the F-111 module and missile stage separation. With a rail and slipper block arrangement, similar to but larger than those used on the CREST and SIII S-3 ejection seats, the system has a low development risk. The HLV pod, with larger blowaway panels but no rails is again impacted by the experimental HLV structural design resulting in increased risk in this area.

All four systems rely on ablative heat-shields that have been used with both manned and unmanned space capsules.

The aerodynamic loads experienced during crew escapes should be similar to those encountered during ballistic and low lift/drag ratio reentries. The heat shields are all, therefore, considered to have low-to-medium development risks.

The major restraint system risk is due to the high, long-duration forward (-x) accelerations that can be experienced under some escape conditions. The major concern is head restraint to prevent neck injuries during high "Q" ejections. Several different head restraint systems have been designed, but none has undergone qualification testing. This system is, therefore, considered to have a moderate risk for the HLV configurations and somewhat less for the VLV systems which do not eject at as high dynamic pressures.

9.6 SAFETY

The differences in the safety rating of different escape concepts are primarily due to the differences in the amounts of propellant corresponding to the various concepts, as the probability of inadvertent ignition or leakage, and the number of actions required for safetying during maintenance are essentially the same for all concepts.

The amounts of propellants for each escape system and the corresponding rating factors for safety are shown in Table 9.6-1. The rating factors were assigned qualitatively using the merit scale of Table 8.4-1. It should be noted that the potential damage due to inadvertent leakage or ignition of propellant does not vary linearly with the amount of propellant. For example, damage due to an inadvertent ignition of 100 pounds of propellant will probably be almost as lethal as that due to inadvertent ignition of 200 pounds of propellant.

9.7 RELIABILITY

The reliability of each escape system was evaluated qualitatively from its probability of a failure. The probability of a failure is considered to be mainly a function of the number and type of subsystems used in the configuration. The reliability ratings of the four configurations were determined using the merit scale of Table 8.4-1 and are listed below on a 0 to 10 scale:

Dual-place encapsulated seat	6.5
HLV pod capsule	5.0
Single-place encapsulated seat	7.0
VLV pod capsule	5.5

The single- and dual-encapsulated seats, have the same general configuration and equipment arrangement. However, the dual seat is equipped with some duplicate systems to accommodate the additional crew member. The additional equipment impacts the reliability of the dual-place encapsulated seat negatively compared to the single-place encapsulated seat.

The HLV pod capsule is more complex from a structures standpoint. The heat shield location and the location of the recovery system appear to add complexity as compared to the VLV pod capsule. The wings and actuators also add complexity to the HLV pod capsule, thereby reducing system reliability. Both pod capsules are more complex than the encapsulated seats.

Table 9.6-1. Rating Factors For Safety

Parameters	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Amount of propellants, lb	182	436	125	248
Rating factor	5.6	5.0	6.0	5.4

9.8 MAINTAINABILITY

The maintainability of each escape system depends on the complexity of the system and the accessibility of the components. These two parameters were evaluated qualitatively using the merit scale of Table 8.4-1. The rationale for the ratings given for maintainability are provided below. The ratings themselves are given in Table 9.8-1.

Structure. The escape modules must be removed regardless of the configuration for inspection and maintenance of the structure. There are more access hatches and surfaces on the HLV pod capsule which means more maintenance compared to the other configurations.

Separation Subsystem. This subsystem is more complex than the other subsystems. Accessibility of pyrotechnic components is about the same for each of the configurations. The escape modules may or may not need to be removed to maintain this system.

Propulsion. The maintenance of the propulsion system is equally complex for all configurations. The encapsulated seats must be removed to inspect and maintain the propulsion subsystem. The pod capsules removal for inspection will be more difficult although access to part of their propulsion systems may be designed to not require complete capsule removal. For example, the HLV pod capsule thrusters could be accessible through the nose wheel bay and the propellant tanks could be accessible by a tunnel from the aft avionics bay. Parts of the VLV pod capsule propulsion system could be mounted on a pallet with access from the rear and be removed through the payload bay.

Life Support. The life support systems are about the same in complexity in all the configurations. The dual-place encapsuled life support system is difficult to inspect or service because of its location. Also, the fact that the pod capsules have ECS on board makes them more difficult to maintain.

Instruments. In the pod capsules, this system seems to be easier to access than the encapsulated seats.

Recovery System. The encapsulated seats and the VLV pod capsule have personal-size parachutes, which are easier to access than the large parachutes on the HLV pod capsule.

Heat Shield. All the configurations use the same Silica Phenolic material for heat shields. The need or the complexity to maintain the heat shields will increase with their size. For the encapsulated seats and the HLV pod capsule, the propulsion units are in the way of accessing the heat shield. For all the configurations, the escape module must be removed from the aircraft for maintenance of this system.

Table 9.8-1. Rating Factors for Maintainability

Subsystems	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Structure	7.0	6.0	8.0	7.0
Separation	6.8	6.0	6.8	6.5
Propulsion	6.0	5.0	6.0	6.0
Life support	7.0	5.0	8.0	6.0
Instruments	6.5	8.0	6.5	7.5
Recovery	7.0	3.0	8.0	7.0
Heat shield	5.0	4.0	6.0	7.0
Power supply	7.5	8.0	7.0	7.0
Survival kit	8.0	8.0	8.0	8.0
Controller/sensors	7.5	7.0	7.0	8.5
Wings/actuation	10.0	5.0	10.0	10.0
Average	7.1	5.9	7.4	7.3

Power Supply. The power requirements are about the same for all configurations. The power supplies will be easy to access in all configurations, with the pod capsule providing the easiest access.

Survival Kit. All the configurations provide easy access to the survival kit.

Controller/Sensors. The access to the controllers/sensors is easy for all the configurations, with the VLV pod capsule providing the best access.

Wings/Actuation. The encapsulated seats and the VLV pod capsule were given a score of 10.0, because these configurations do not have any wings. The HLV pod capsule will have to be removed to access this system.

9.9 DEVELOPMENT COST

The development costs for the various crew escape concepts were assumed to be proportional to the adjusted weights, development risks, and vehicle integration work associated with these concepts.

The adjusted weights for the escape concepts were equal to the weight penalties of the concepts (Table 9.2-1) minus the survival kits.

For the purpose of calculating the development costs, the values of the development risk and vehicle integration work associated with various escape concepts were taken as inversely proportional to the corresponding rating factors in Tables 9.5-1 and 9.4-1 respectively.

The calculations of the relative development costs, with the cost for a single-place encapsulated seat normalized to 1, are shown in Table 9.9-1. These indicate that if the development cost of a single-place encapsulated seat is estimated to be about 100 million dollars, then the development costs for the dual-place encapsulated seat, HLV pod capsule and the VLV pod capsule, can be estimated to be about 180 million, 344 million, and 169 million dollars respectively.

The rating factors for development cost were calculated by using the curve in Figure 8.4-7 for high cost items, and are shown in Table 9.9-1. These rating factors can also be calculated by using the equivalent equation given below:

$$\text{Rating factor} = 6 - 6 \log (\text{cost/geometric mean})$$

9.10 PRODUCTION COST

The production costs for the various escape system concepts were considered to be proportional to their adjusted weights, as defined in Section 9.9. The calculations of the

Table 9.9-1. Rating Factors for Development Cost

Parameters	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Adjusted weight	1072	2346	704	1387
Rating factor for development risk	5.80	6.10	6.20	7.00
Rating factor for vehicle integration	5.70	6.20	6.30	6.50
Relative cost	1.80	3.44	1.00	1.69
Cost/geometric cost	1.00	1.91	0.55	0.94
Rating factor	6.00	4.30	7.50	6.10

relative production costs, with the cost for a single-place encapsulated seat normalized to 1, are shown in Table 9.10-1. The rating factors for production cost were also calculated using the curve in Figure 8.4-7 for high cost items and are also shown in Table 9.10-1.

9.11 LOGISTICS

The four escape system concepts are similar in complexity and logistics requirements are assumed to be the same. For example, required maintenance training and skills are expected to be the same. The materials used to fabricate the heat shields and structure will require the same maintenance skills to maintain. The numbers of maintenance personnel required will vary depending on weight, size, failure rates, and accessibility of installed equipment. The pod capsules will have increased support equipment requirements for removal and ground handling over the encapsulated seats. The dual-seat configuration will require special handling equipment as compared to the single-seat configuration.

The rating factors were determined using the merit scale and are provided in Table 9.11-1.

Table 9.10-1. Rating Factors for Production Cost

Parameters	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Adjusted weight	1072	2346	704	1387
Relative cost	1.52	3.33	1.00	1.83
Cost/geometric mean	0.87	1.91	0.57	1.05
Rating factor	6.30	4.30	7.40	5.90

Table 9.11-1. Rating Factors for Logistics

Evaluation factors	Dual-place encapsulated seat	HLV pod capsule	Single-place encapsulated seat	VLV pod capsule
Maintenance skill	7.0	7.0	7.0	7.0
Maintenance personnel	7.0	5.0	8.0	6.0
Special equipment	8.0	4.0	8.0	5.0
Special tools	8.0	8.0	8.0	8.0
Spares	7.0	5.0	8.0	6.0
Average	7.4	5.8	7.8	6.4

10.0 CONCLUSIONS AND RECOMMENDATIONS

The conceptual development, technologies investigation, subsystem design, performance analysis and trade study conducted of the various alternative HVT escape system concepts, and described in this report, lead to the following conclusions and recommendations:

a. Both the escape capsules and the encapsulated seats with appropriate thermal protection are viable options for providing emergency crew escape over the whole flight regime of the hypervelocity vehicles capable of orbital flight. Many other escape concepts were evaluated, but as discussed in Section 4.0, these could provide the desired escape capability over only part of the flight regime.

b. On the basis of the design criteria used in the trade study, the encapsulated seats were overall superior to the pod capsules for HLV as well as VLV. As may be noted from the design decision matrix in Table 9.0-1, the total score was 6.86 for the dual-place encapsulated seat compared with 5.03 for the pod capsule for the HLV. Similarly, the total score was 7.11 for the single-place encapsulated seat compared with 5.58 for the pod capsule for the VLV.

   The biggest factor contributing to the superiority of the encapsulated seats was the associated weight penalty. The weight penalty for the dual-place encapsulated seat was 1132 pounds compared with 2406 pounds for the pod capsule for the HLV (Table 9.2-1). Similarly, the weight penalty for the single-place encapsulated seat was 734 pounds compared with 1417 pounds for the pod capsule for the VLV.

c. Advances in high temperature structural materials and ablative materials are required to bring the weight penalties for the HVT escape concepts down to more acceptable levels. Even in case of the overall superior encapsulated seats, the weight penalty due to heat shield was 260 pounds for the dual-place seat and 170 pounds for the single-place seat.

d. The gelled propellants offer significant weight advantage over solid propellants or cryogenic fuels for the HVT escape system concepts. However, more development work is required to establish their safety, long-term stability under temperature cycling with vibration, and rheological properties over the expected shear rates and temperatures. A propulsion system using gelled propellants needs also to be designed and tested on an ejection seat or an escape capsule to develop and demonstrate the basic hardware, including that for thrust-vectoring control.

e. Providing inherent aerodynamic stability of an encapsulated seat or an escape capsule can result in significant weight reduction of its attitude control system. Wind tunnel testing at high speeds, complemented by better methods for estimating aerodynamic characteristics, should be used to establish the aerodynamic coefficients for the basic concept configurations, and then to evaluate the benefits of installing appropriate aerodynamic surfaces for improved stability.

f. Accurate dynamic simulations of orbital escape conditions required excessively high computation times, when using earth-centered inertial x-y-z coordinate frame. Alternative simulation models need to be developed to reduce computation time to acceptable levels.

g. The thermal protection requirements for the crew escape systems can be minimized by selecting optimal trajectories during re-entry into atmosphere. Such optimal trajectories and the corresponding control laws should be developed so that the weight penalty due to the heat shield can be minimized.

h. Simple roll control of each HVT escape concept provided some crossrange capability during hypersonic escape, the exact value depending upon the corresponding lift to drag ratio. A more refined control law needs to be developed for achieving optimum crossrange during hypersonic escape without causing yaw or roll instability of the escape system.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Reference Area
ACC	Advanced Carbon-Carbon
ACECT	Advanced Crew Escape Capsule Technologies
ACES	Advanced Concept Ejection Seat
ACS	Attitude Control System
AFRPL	Air Force Rocket Propulsion Laboratory
AIM	Automatic Inflation Modulation
BASC	Boeing Advanced Systems Company
BMAC	Boeing Military Airplane Company
BTPS	Body Temperature Pressure Saturated
CAT	Cockpit Automation Technology
CD	Drag Coefficient
CDRL	Contract Data Requirements List
CG	Center of Gravity
CHABA	Committee on Hearing and Bio-Acoustics
CL	Lift Coefficient
CNS	Central Nervous System
CONUS	Continental United States
CO_2	Carbon Dioxide
CREST	Crew Escape System Technologies
D	Drag
DCS	Decompression Sickness
DEP	Design Eye Point
ECLSS	Environmental Control and Life Support System
ECS	Environmental Control System
ESG	Electrostatically Suspended Gyros
EVA	Extra Vehicular Activity
fps	Feet Per Second

g	Gravitational Acceleration
GAP	Glicidyl Azide Polymer
GPS	Global Positioning System
Hg	Mercury
HLV	Horizontally Launched Vehicle
HTPB	Hydroxy-Terminated Polybutadiene
HUD	Head-Up Display
HVT	Hypervelocity Technology
INS	Inertial Navigation System
KEAS	Knots Equivalent Airspeed
L	Lift
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
LSC	Linear Shaped Charge
MADAN	Multimission Altitude Determination and Autonomous Navigation
MFD	Multifunction Display
MSIS	Man/System Integration Standards
MSL	Mean Sea Level
NAS-NRC	National Research Council of the National Academy of Sciences
NASP	National Aerospace Plane
NTPD	Normal Temperature Pressure Dry
PDM	Pulse Duration Modulation
PLZT	Plumblum Lanthalum Zirconate Titanate Ceramic Wafers
psf	Pound Per Square Feet
PSF	Pounds Per Square Feet
PTS	Permanent Threshold Shift
RCC	Reinforced Carbon-Carbon
RCS	Reaction Control System
RLG	Ring Laser Gyros

SHAD	Stellar Horizon Atmospheric Dispersion
SHAR	Stellar Horizon Atmospheric Refraction
SOW	Statement of Work
SMS	Space Motion Sickness
SRS	Space Rescue Station
SSME	Space Shuttle Main Engine
TFOV	Total Field of View
TLSS	Tactical Life Support System
TTS	Temporary Threshold Shift
TVC	Thrust-Vector Control
UPCO	Universal Propulsion Company
USAF	United States Air force
VLV	Vertically Launched Vehicle
W	Weight

APPENDIX A. SHORT-TERM ACCELERATION EXPOSURE LIMITS

The following discussion on short term acceleration limits is an excerpt from the SOW for USAF contract F33615-86-C-3410 (Reference 7).

1. **Acceleration Limits Reference System.** The translational and angular motion of the escape system shall be constrained so that the translation acceleration components of the motion acting at a single Critical Point are limited by the criteria specified in Paragraphs 3 and 4 with maximum rotational rates limited as defined in Paragraph 5. The coordinate system and the dimensions that define the location of the Critical Point are given in Figure A-1.

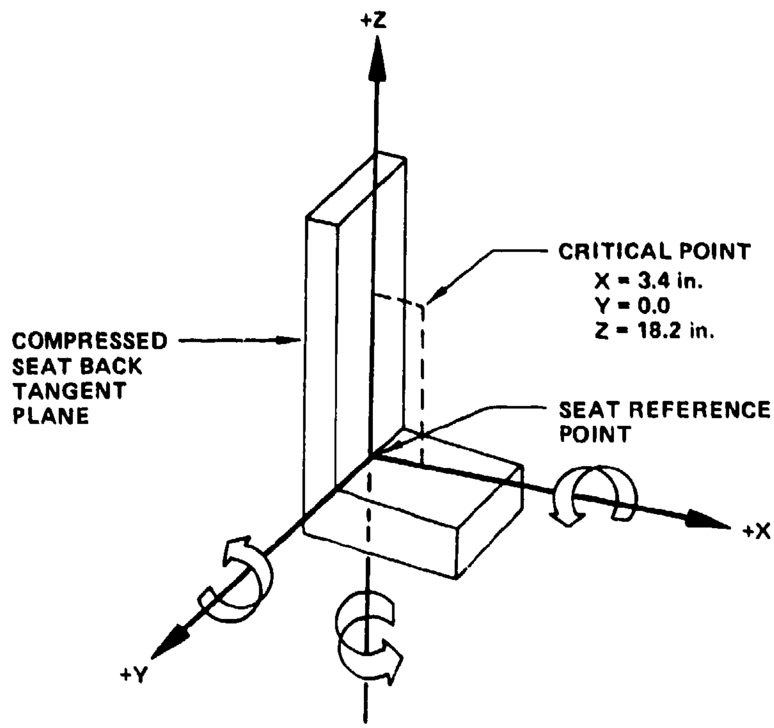
2. **Acceleration Evaluation Method.** The acceptability of the accelerations at the Critical Point shall be evaluated by computing the Dynamic Response (DR) as a function of time for each major axis (X, Y, and Z). The DR is computed using the following equations:

$$\ddot{\delta} + 2\zeta\omega_n\dot{\delta} + \omega_n^2\delta = \ddot{s}$$

$$DR(t) = \frac{\omega_n^2\delta(t)}{g}$$

where:

- $\ddot{\delta}$ is the acceleration of the Dynamic Response model mass relative to the Critical Point acceleration (ft/sec^2).
- $\dot{\delta}$ is the relative velocity between the Critical Point and the model mass (ft/sec).
- δ is the compression of the model spring (ft).
- ζ is the damping coefficient ratio (0.2 for the x and y axes and 0.224 for the z axis).
- ω_n is the undamped natural frequency of the model (62.8 rad/sec for the x and y axes and 52.9 rad/sec for the z axis).
- $\ddot{s}$ is the acceleration component along the pertinent axis acting at the Critical Point (ft/sec^2).
- g is the acceleration due to gravity (32.2 ft/sec^2).
- (t) indicates that the parameter is determined as a function of time.



NOTES:

1. THE ORIGIN OF THE PHYSIOLOGICAL COORDINATE SYSTEM IS AT THE SEAT REFERENCE POINT (S.R.P)
2. THE Y-Z PLANE OF THE COORDINATE SYSTEM IS THE COMPRESSED SEAT-BACK-TANGENT PLANE

Figure A-1. Physiological Coordinate System and the Location of the Acceleration-limit Critical Point

3. **Multiaxial Acceleration Limits.** The multiaxial accelerations acting at the Critical Point from the instant of ejection initiation to the instant of seat and seat occupant separation during the recovery phase shall be limited to satisfy the following equation:

$$\sqrt{\left(\frac{DRX(t)}{DRX_L}\right)^2 + \left(\frac{DRY(t)}{DRY_L}\right)^2 + \left(\frac{DRZ(t)}{DRZ_L}\right)^2} \leq 1.0$$

where:

The suffix L denotes the limiting value for the assigned injury risk value.

DRX is the Dynamic Response computed from the X axis acceleration component at the Critical Point.

DRY is the Dynamic Response computed from the Y axis acceleration component at the Critical Point.

DRZ is the Dynamic Response computed from the Z axis acceleration component at the Critical Point.

4. The DR limit values are given in the following table.

	DRX_L		DRY_L		DRZ_L	
	$\ddot{S}_x > 0$	$\ddot{S}_x < 0$	C.R.*	S.P.**	$\ddot{S}_z > 0$	$\ddot{S}_z < 0$
Low Risk	35	23	12	15	15.2	9.0
Moderate Risk	40	30	15	20	18.0	12.0
High Risk	46	35	20	30	22.8	15.0

where:

$\ddot{S}_x$ is the acceleration component along the x axis.

* The column of limits values designated C.R. shall be used if conventional restraint such as a lap belt, two shoulder straps, and crotch strap restrains the seat occupant.

** The column of limit values designated S.P. are permitted if side panels or equivalent structures are used to prevent sideward movement of the seat occupant including the occupant's head.

These limit values are based on experimental data where the seat occupant is restrained by lap belt, shoulder straps, and a strap or straps to prevent submarining of the occupant's pelvis. The +Z axis limits assume that the seat cushion materials do not amplify the acceleration transmitted to the seat occupant. The escape system shall be designed to preserve these assumptions.

5. **Short Duration Angular Velocity Limits.** In addition to the constraints on seat motion specified in Paragraphs 3 and 4, the maximum angular velocities of the seat shall not exceed the values for short duration exposures (less than about one second) specified in the following table.

	Pitch (Rad/Sec)	Yaw (Rad/Sec)	Roll (Rad/Sec)
Low Risk	17.0	18.9	17.0
Moderate Risk	19.7	31.4	19.7
High Risk	22.0	44.0	22.0

APPENDIX B. EXAMPLE DYNAMIC SIMULATION RESULTS

The performance of the various HVT escape system concepts was evaluated by conducting their dynamic simulations using EASY5 program (Reference 23) for the escape conditions shown in Table 9.1-1. As examples, the dynamic simulation results for a single-place encapsulated seat are shown in Figures B-1 through B-12 for escape condition 3 and in Figures B-13 through B-20 for escape condition 4. These escape conditions have the following characteristics at escape instruction:

	Conditions 3	Conditions 4
Altitude, ft.	600	300,000
Speed, ft/sec	422	0
Pitch angle, deg	-10	0
Roll angle, deg	180	0
Sideslip angle, deg	0	0
Flight path angle, deg	-10	0

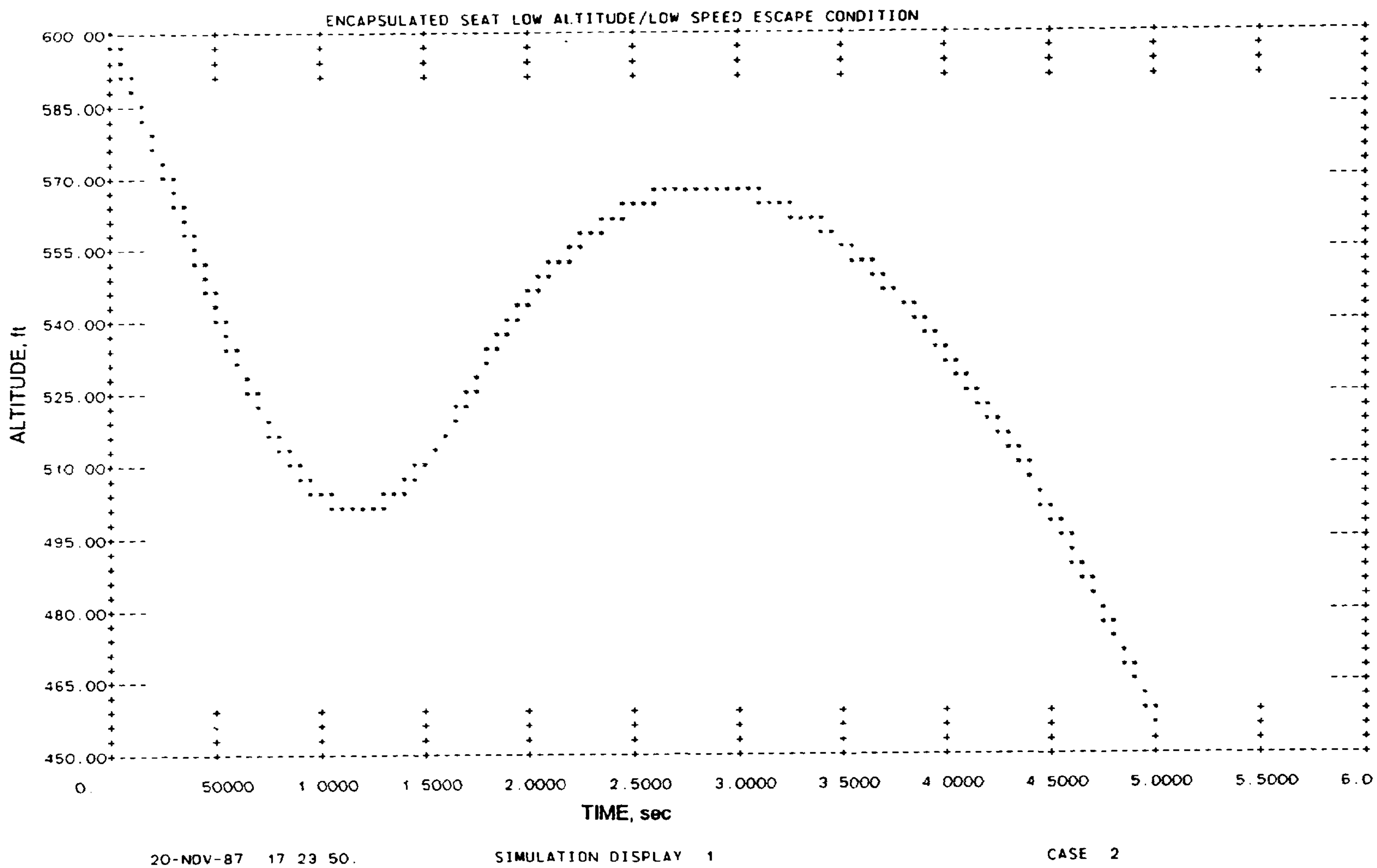


Figure B-1. Altitude Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

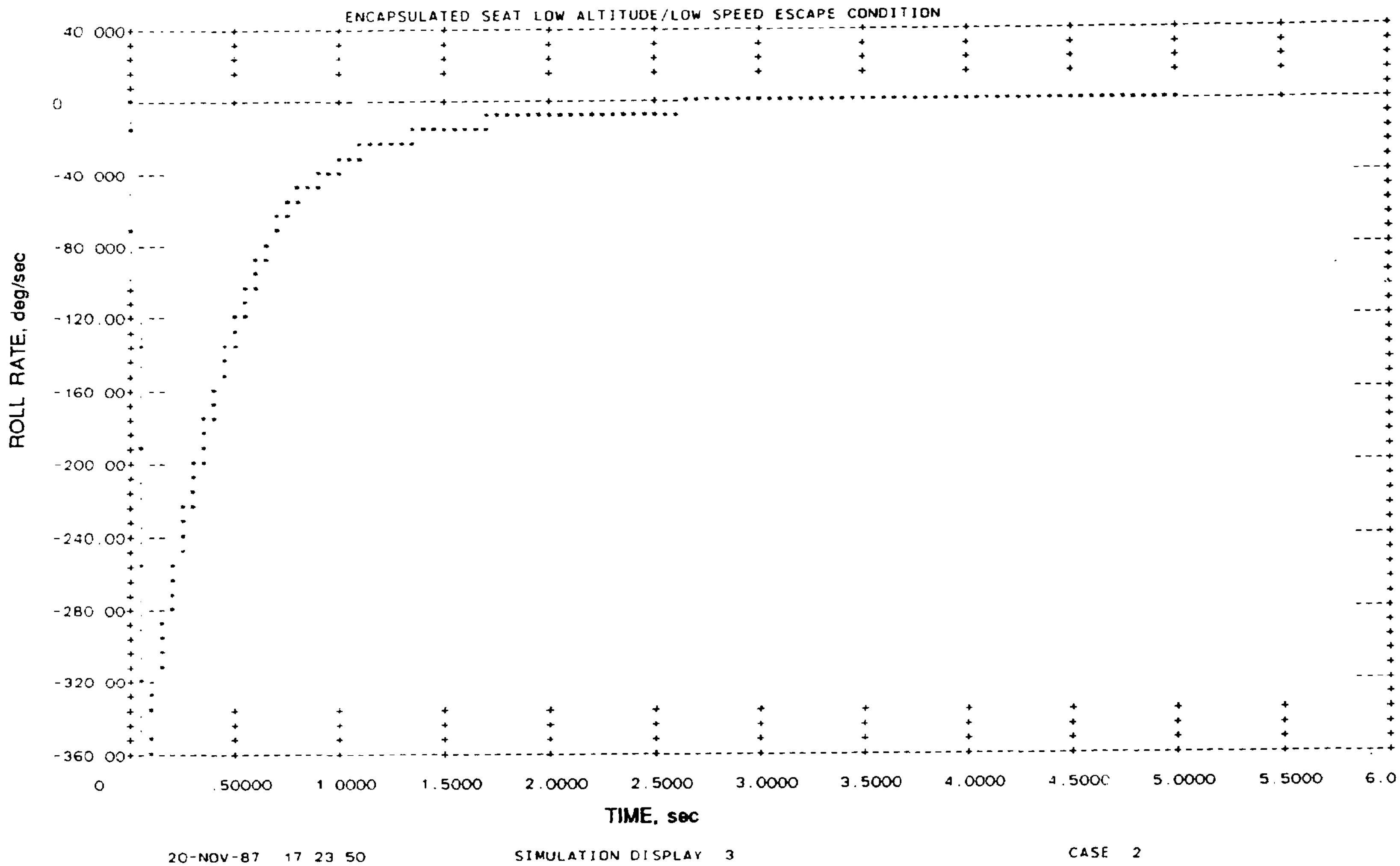


Figure B-2. Roll Rate Versus Time for Single-Piace Encapsulated Seat, Escape Condition 3

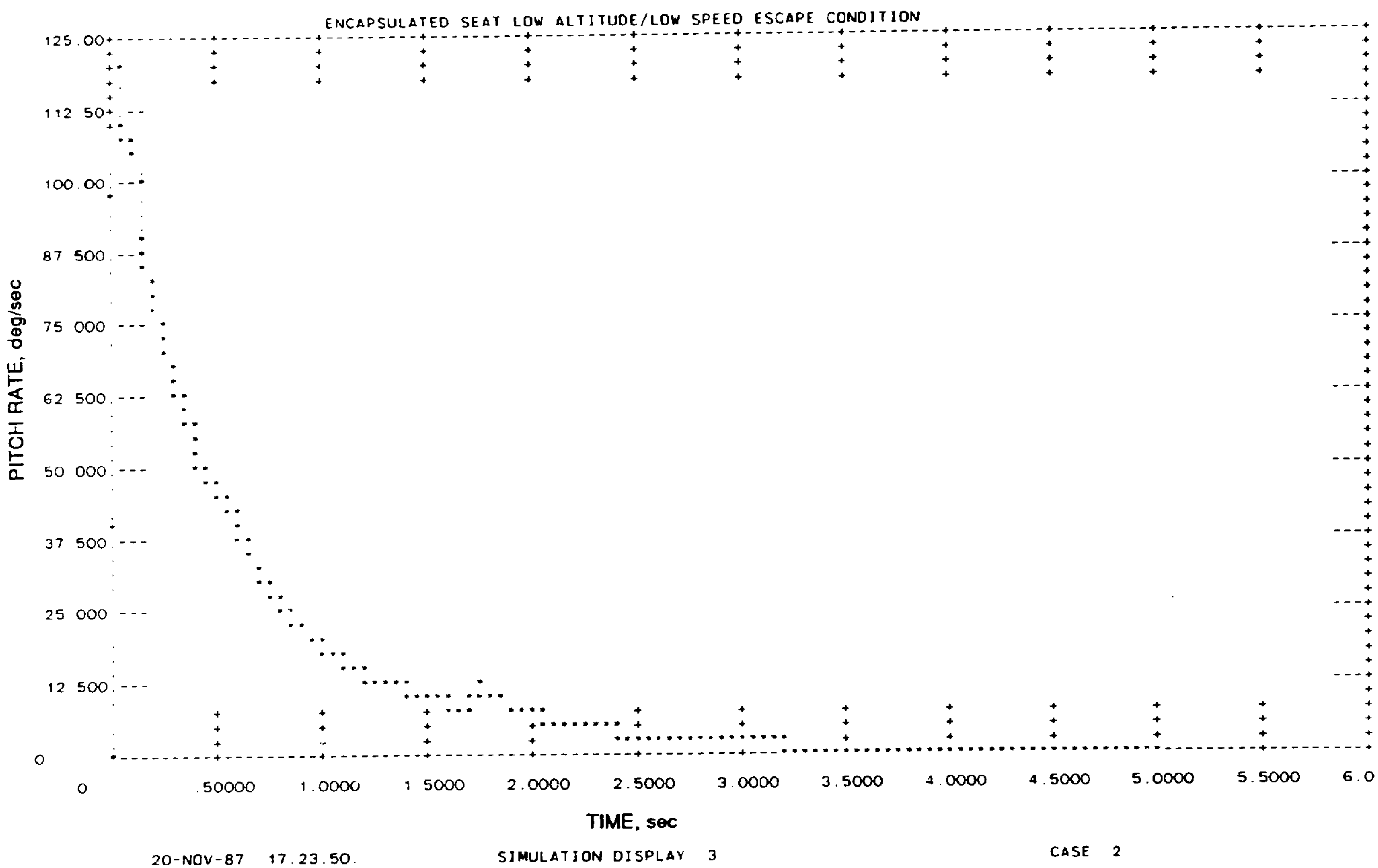


Figure B-3. Pitch Rate Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

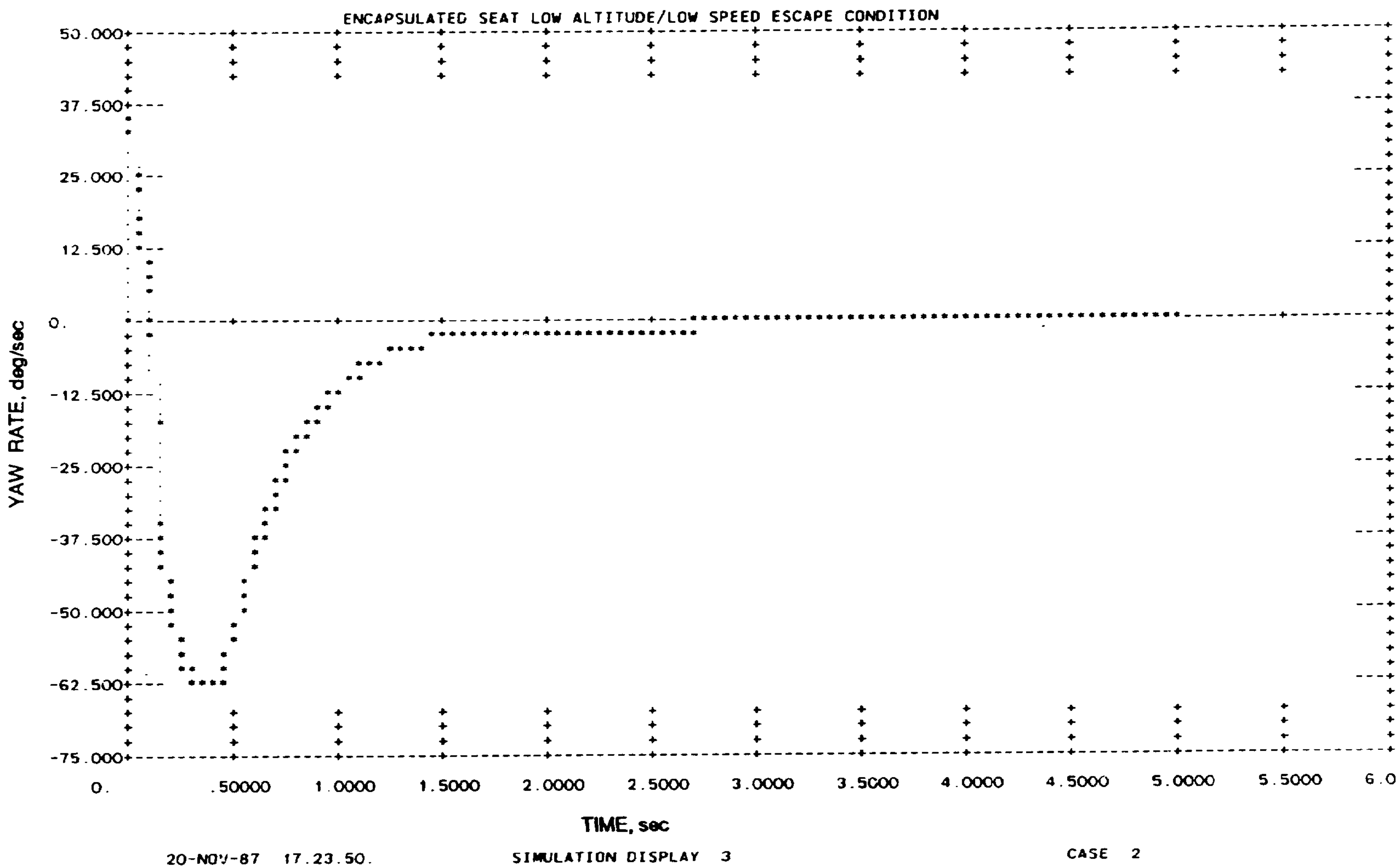


Figure B-4. Yaw Rate Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

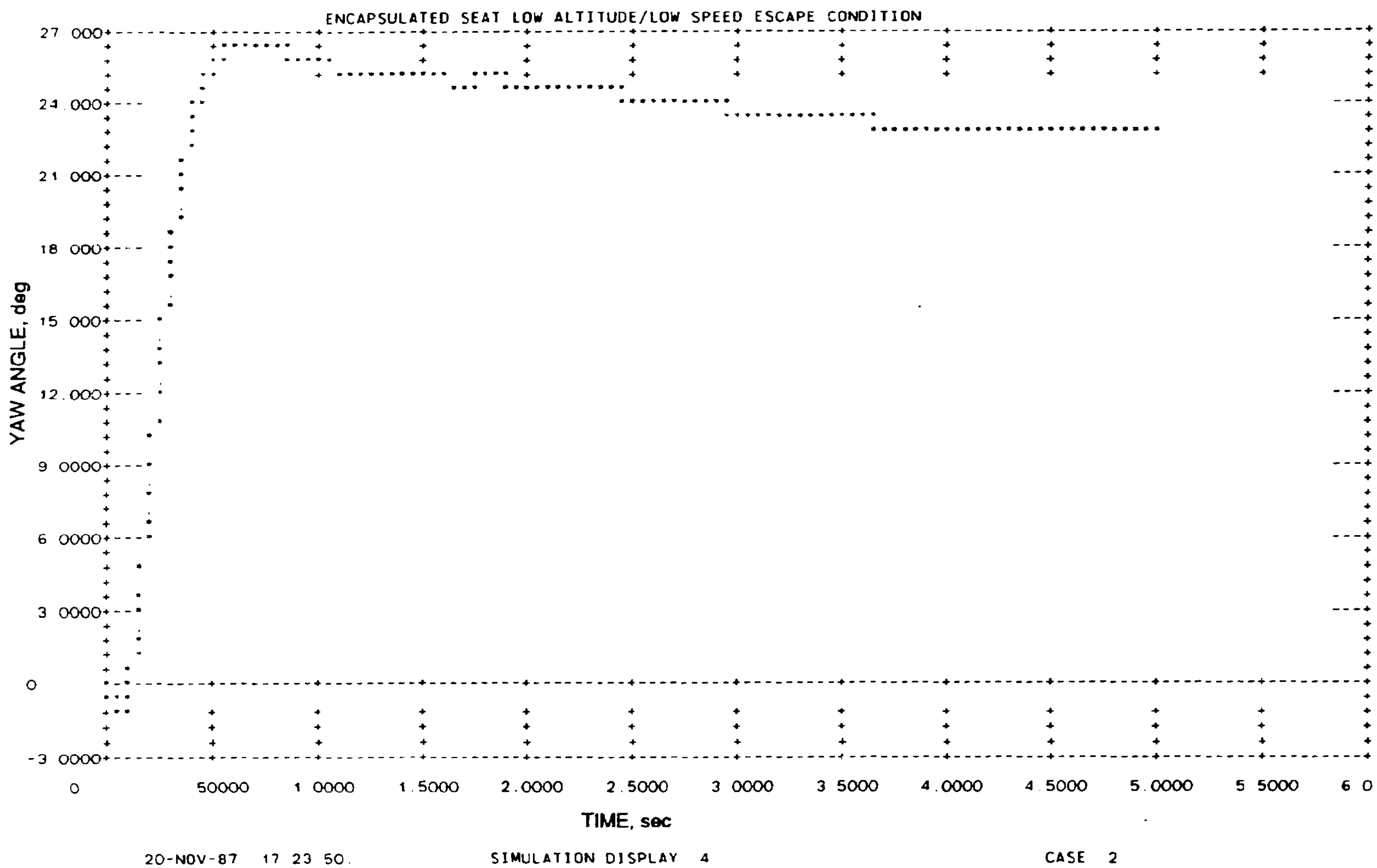


Figure B-5. Yaw Angle Versus Time for Single-Place Encapsulated Seat, Escape Conditon 3

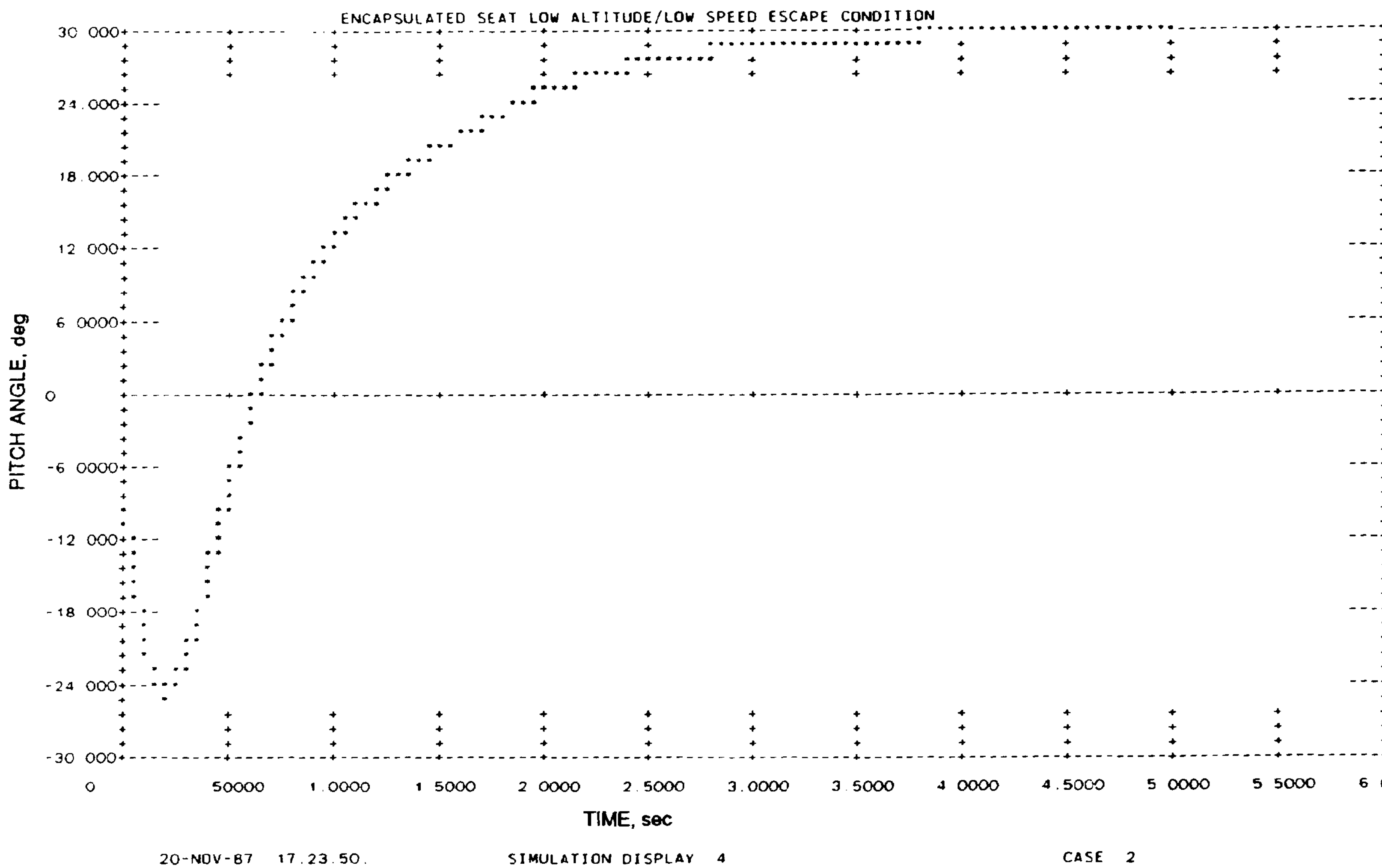


Figure B-6. Pitch Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

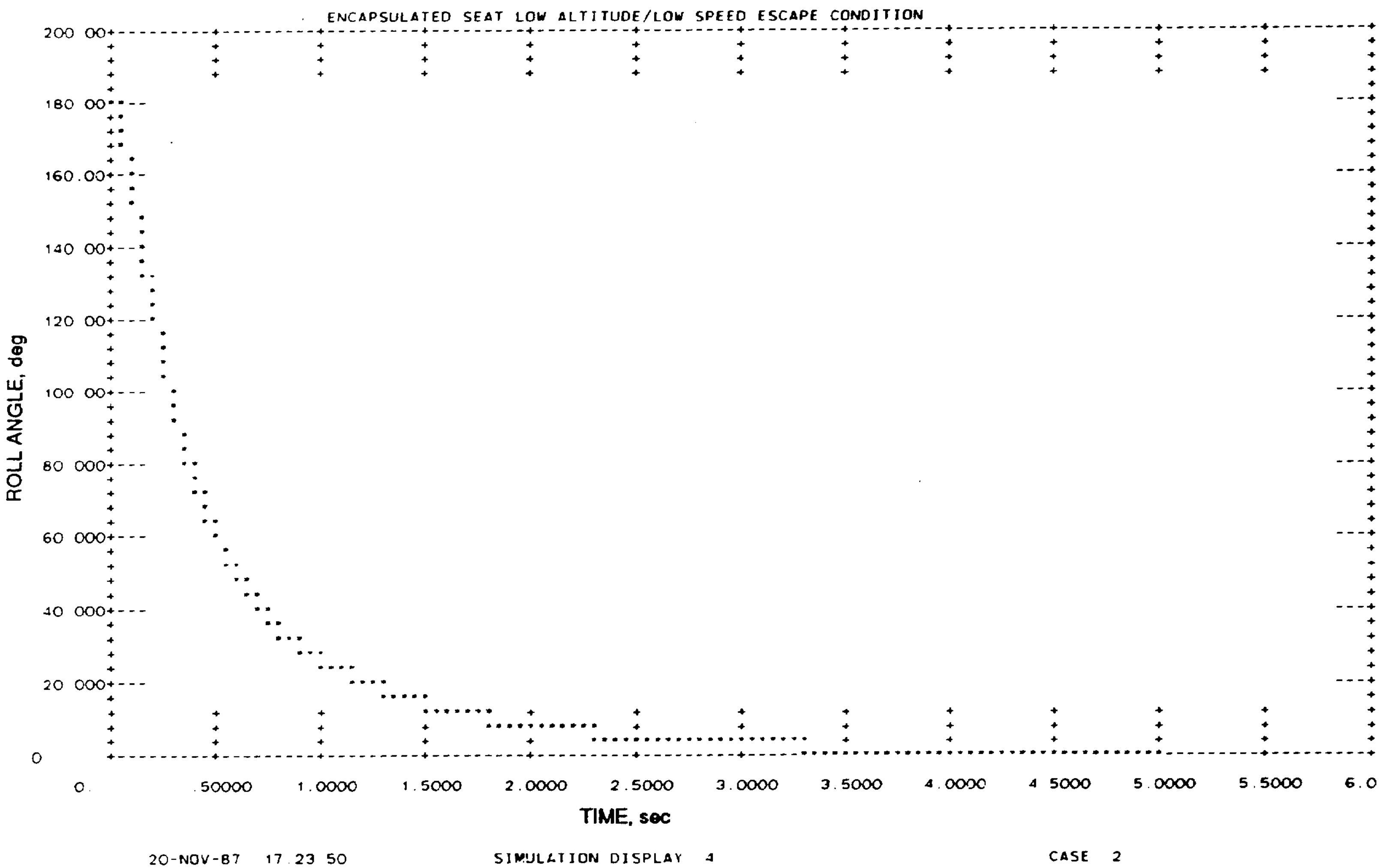


Figure B-7. Roll Angle Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

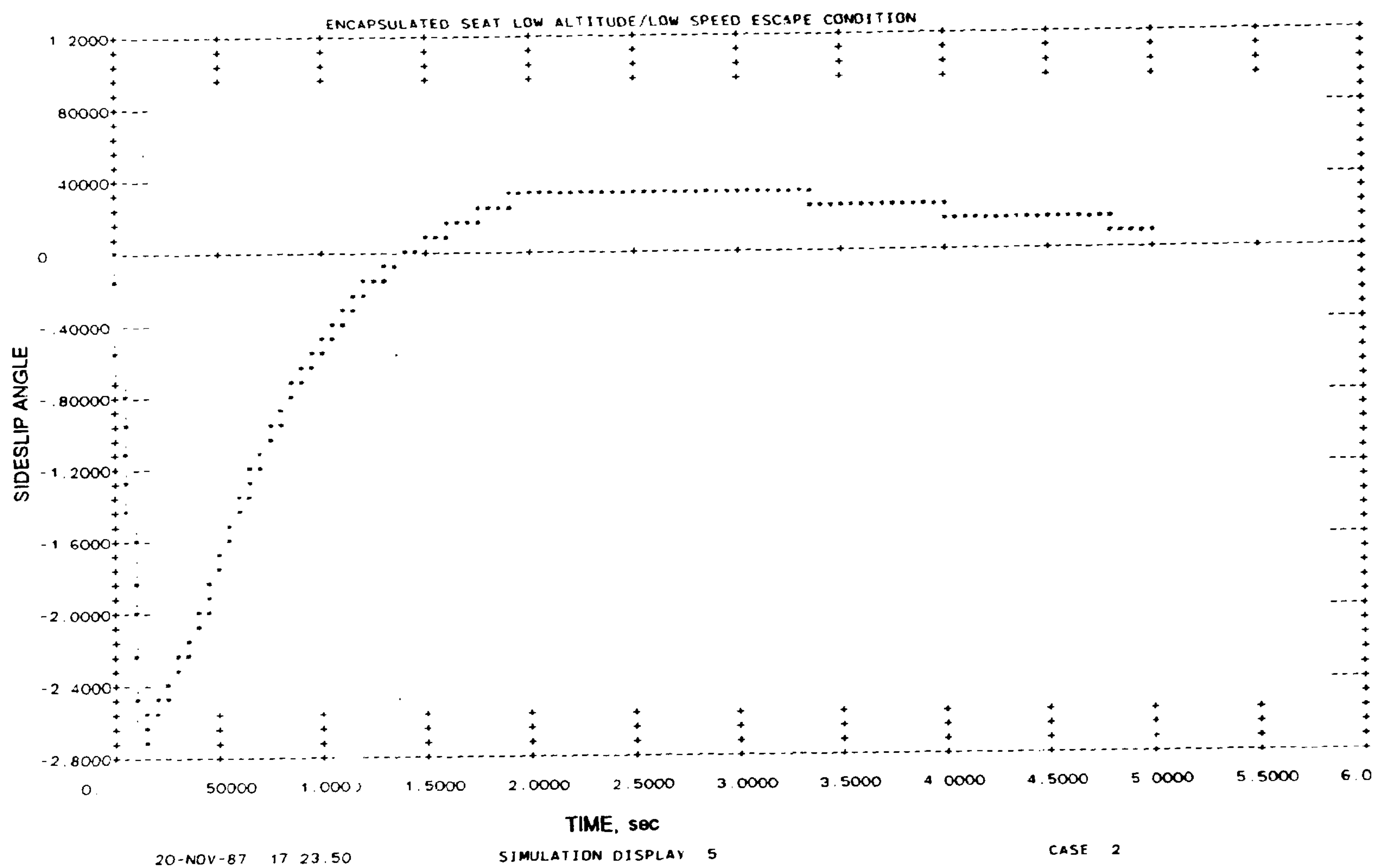


Figure B-8. Sideslip Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

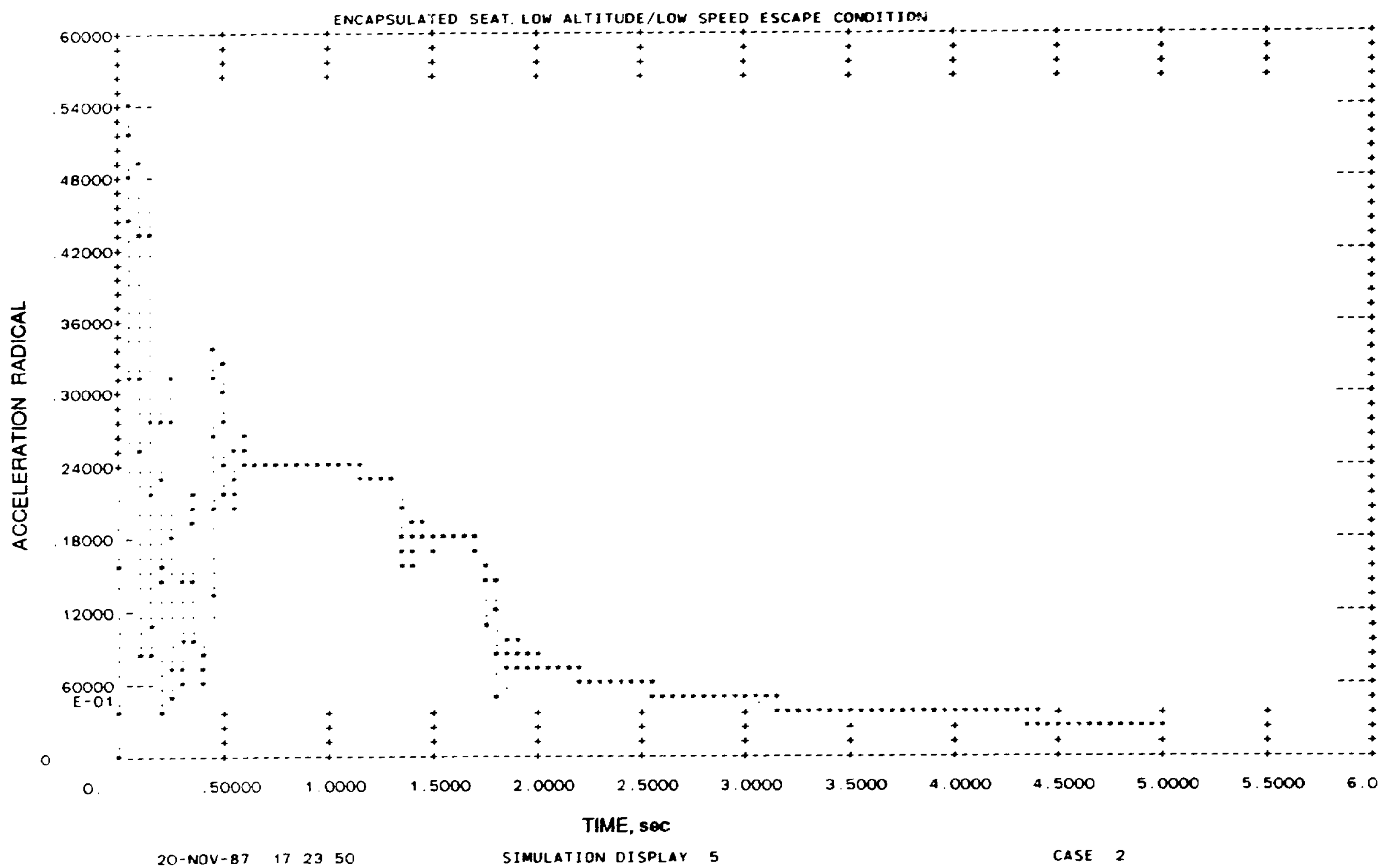


Figure B-9. Acceleration Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

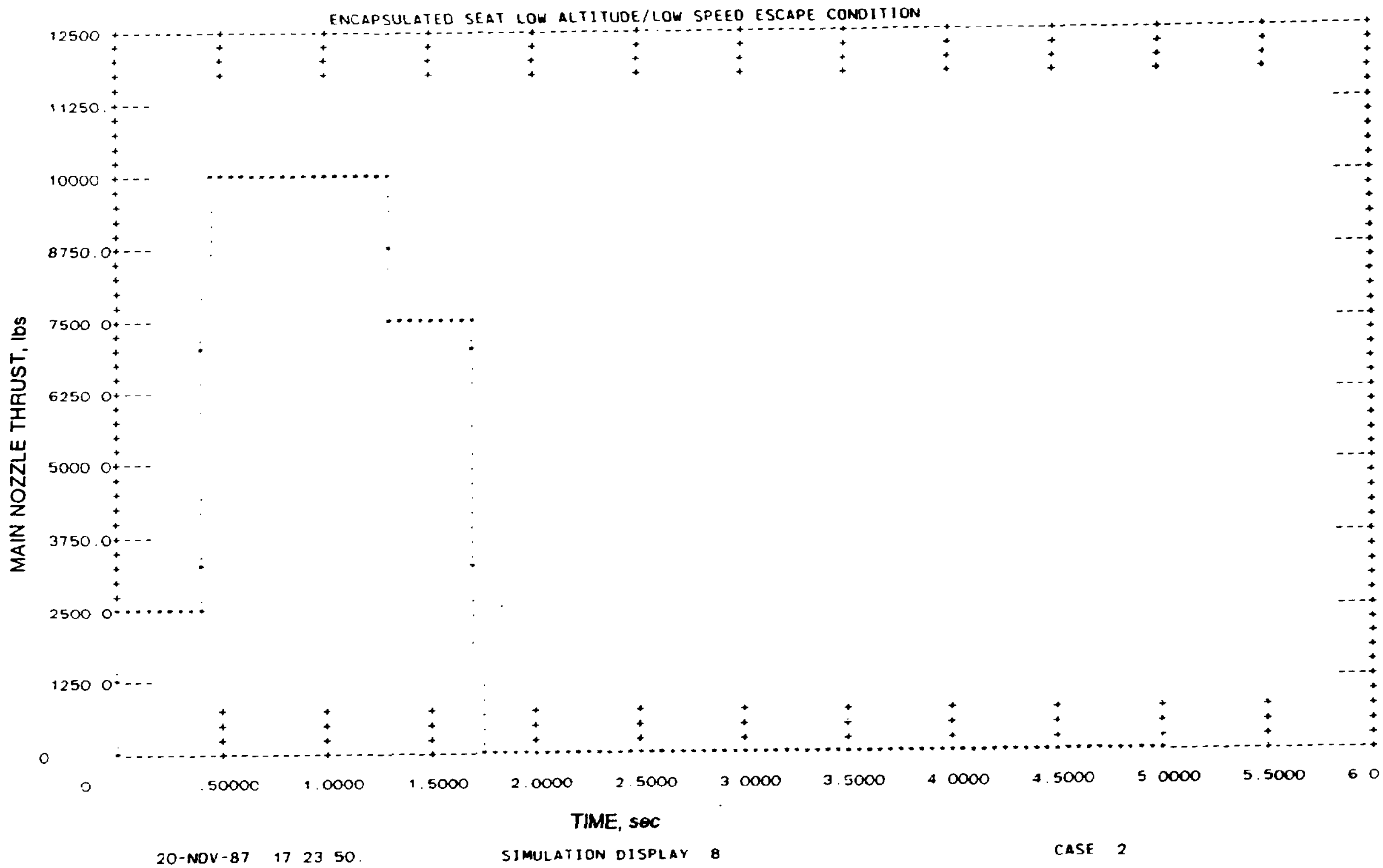


Figure B 10. Main Nozzle Thrust Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

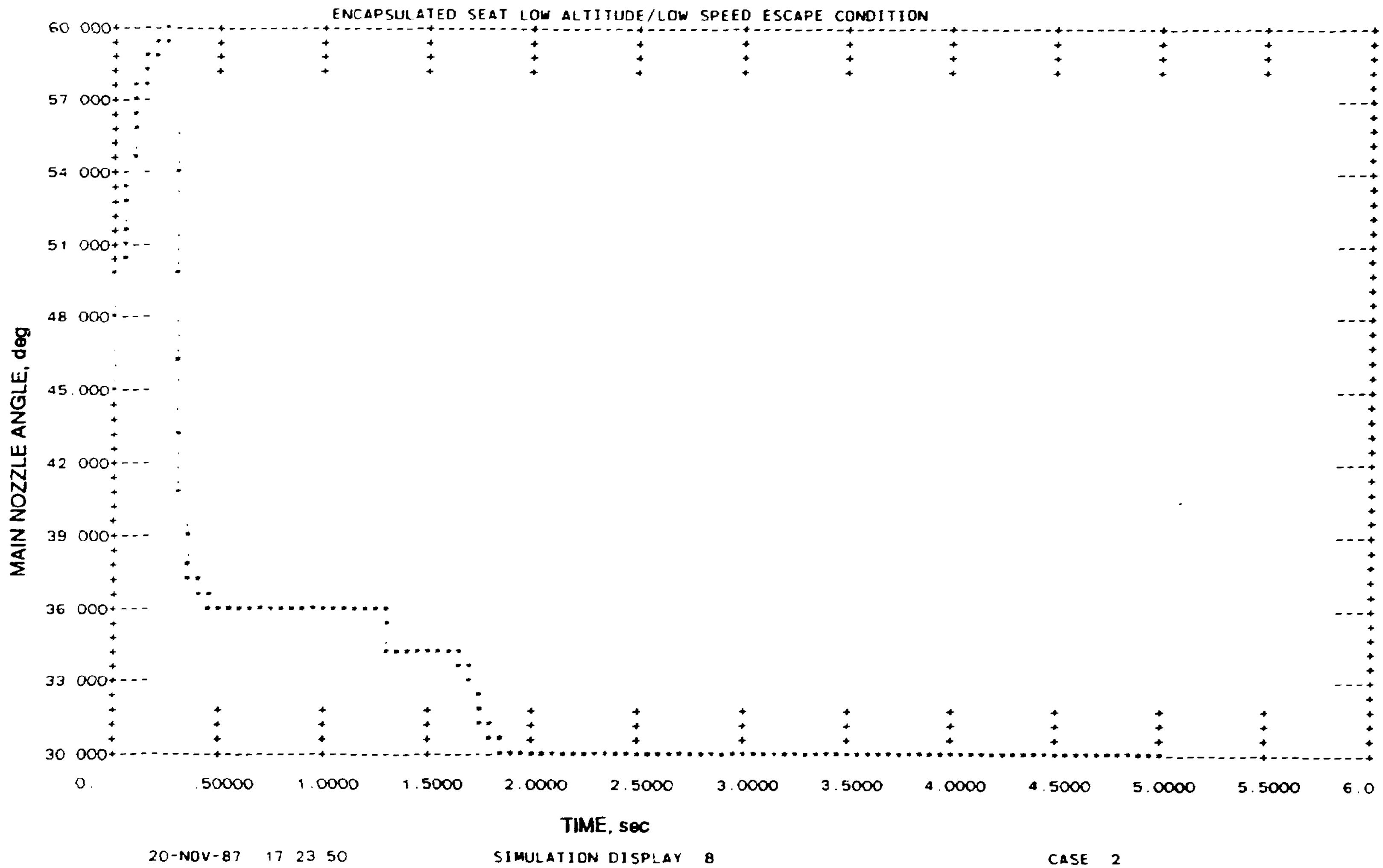


Figure B-11. Main Nozzle Angle Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

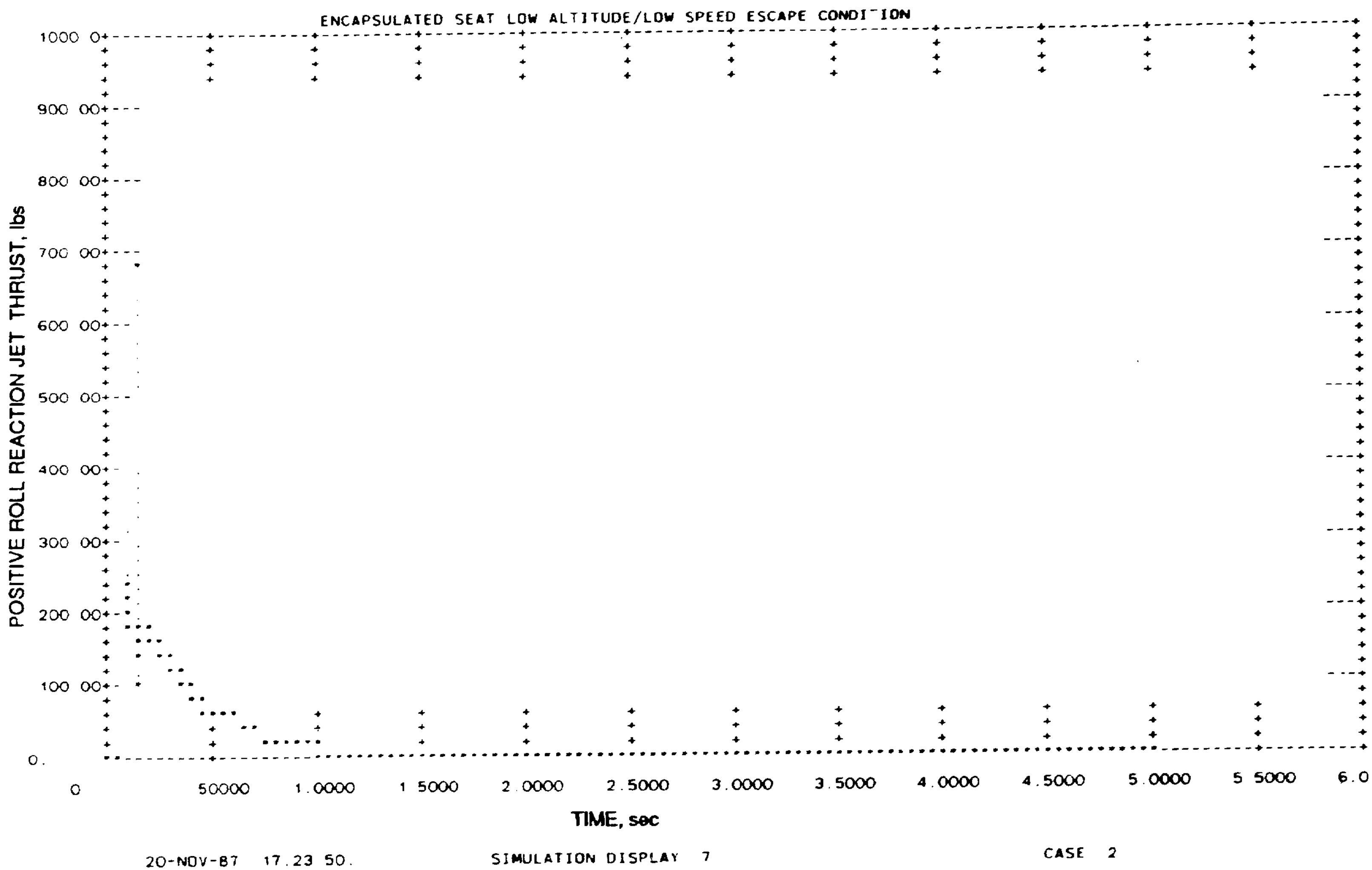


Figure B-12. Positive Roll Reaction Jet Thrust Versus Time for Single-Place Encapsulated Seat, Escape Condition 3

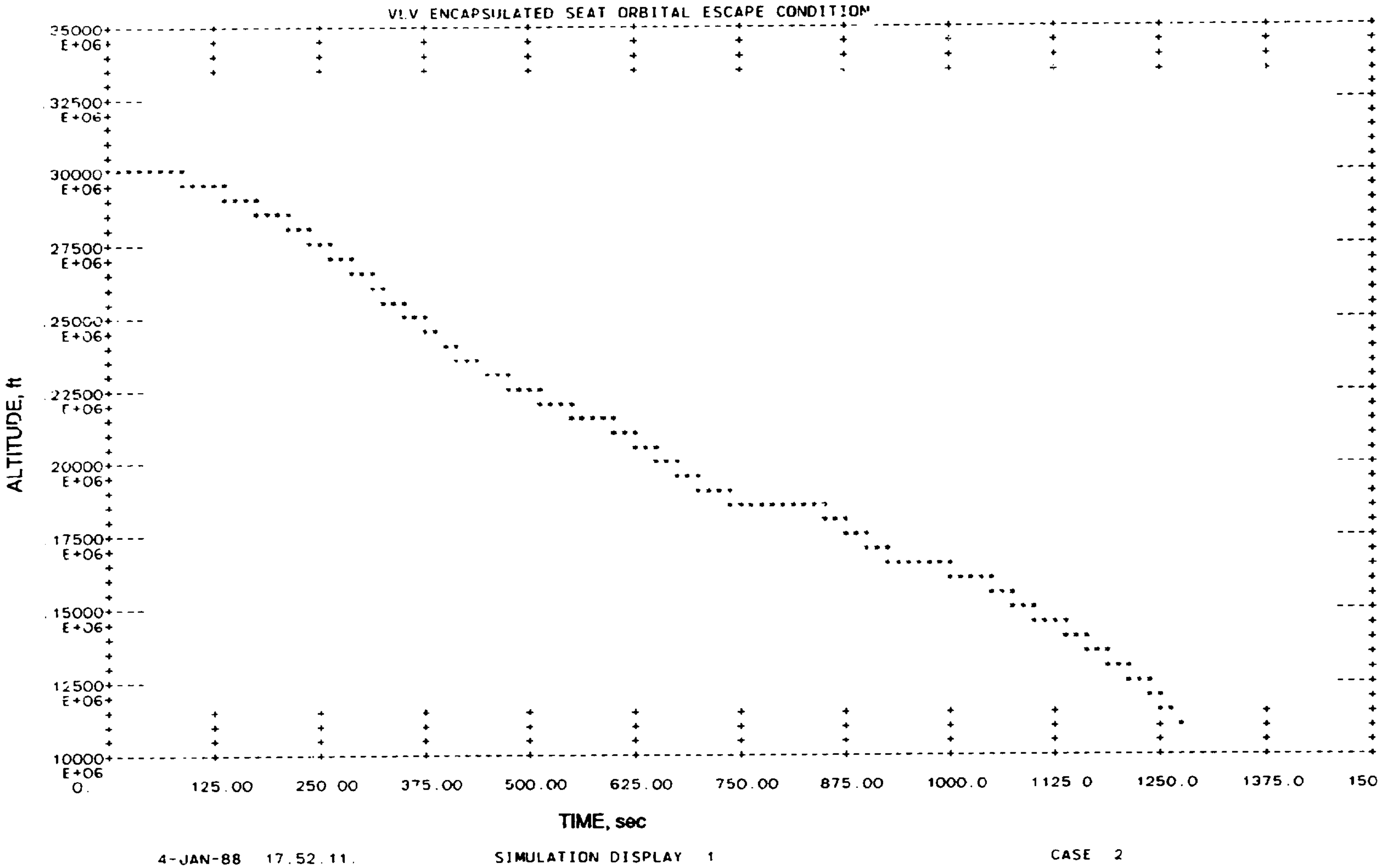


Figure B-13. Altitude Versus Time for Single-Place Encapsulated Seat, Escape Condition 4

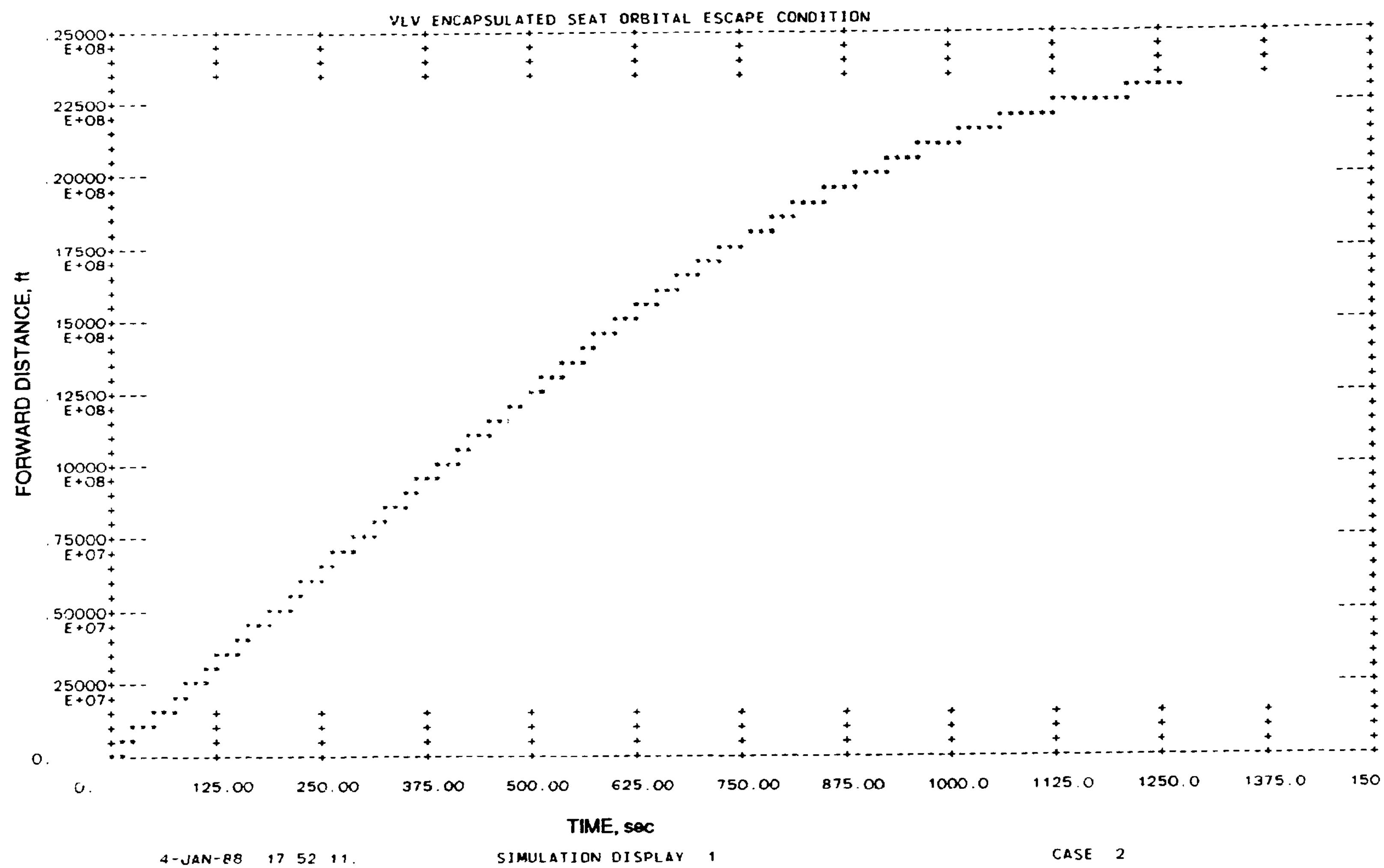


Figure B-14. Forward Distance Versus Time for Single-Place Encapsulated Seat, Escape Condition 4

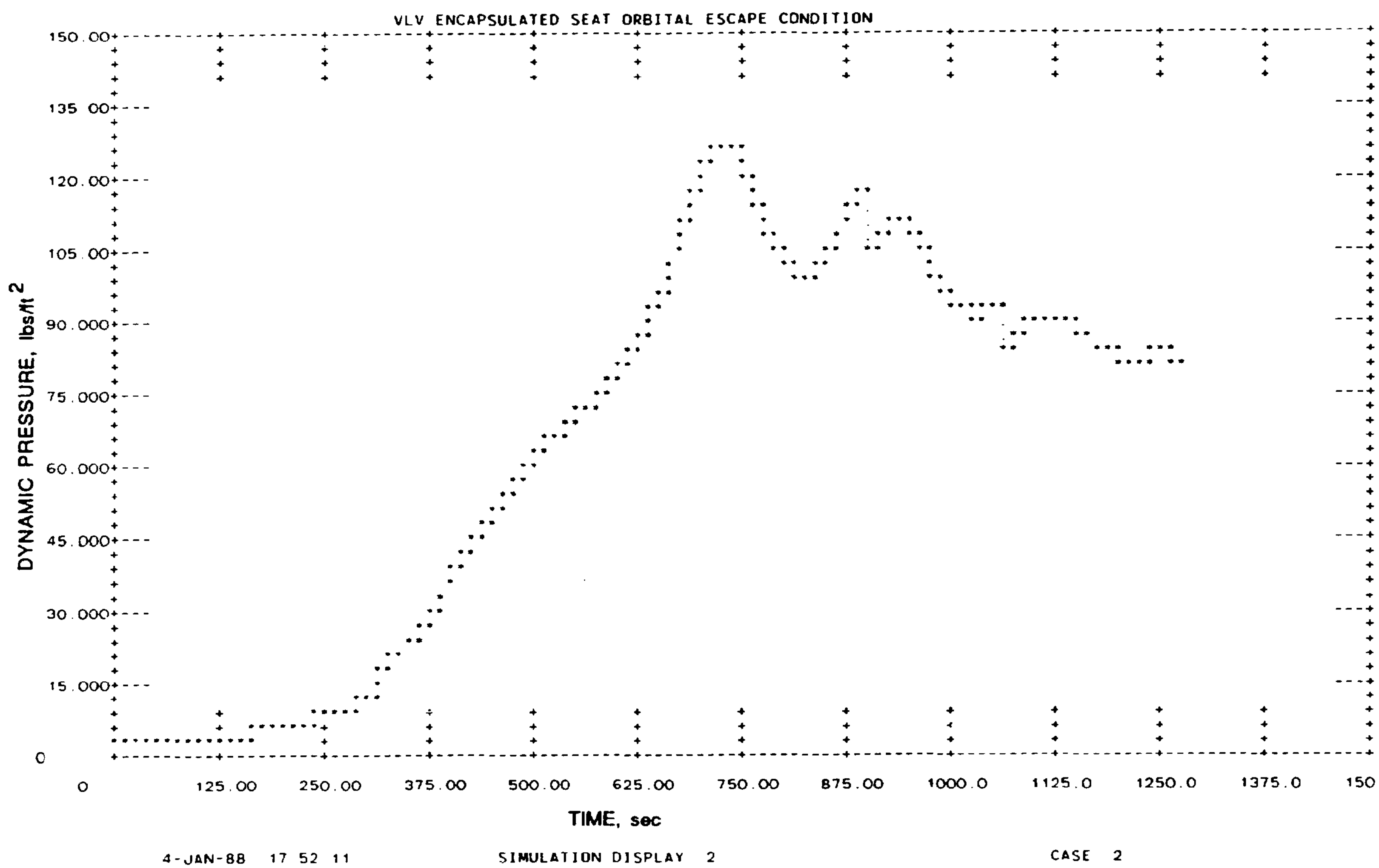


Figure B-15. Dynamic Pressure Versus Time for Single-Place Encapsulated Seat, Escape Condition 4

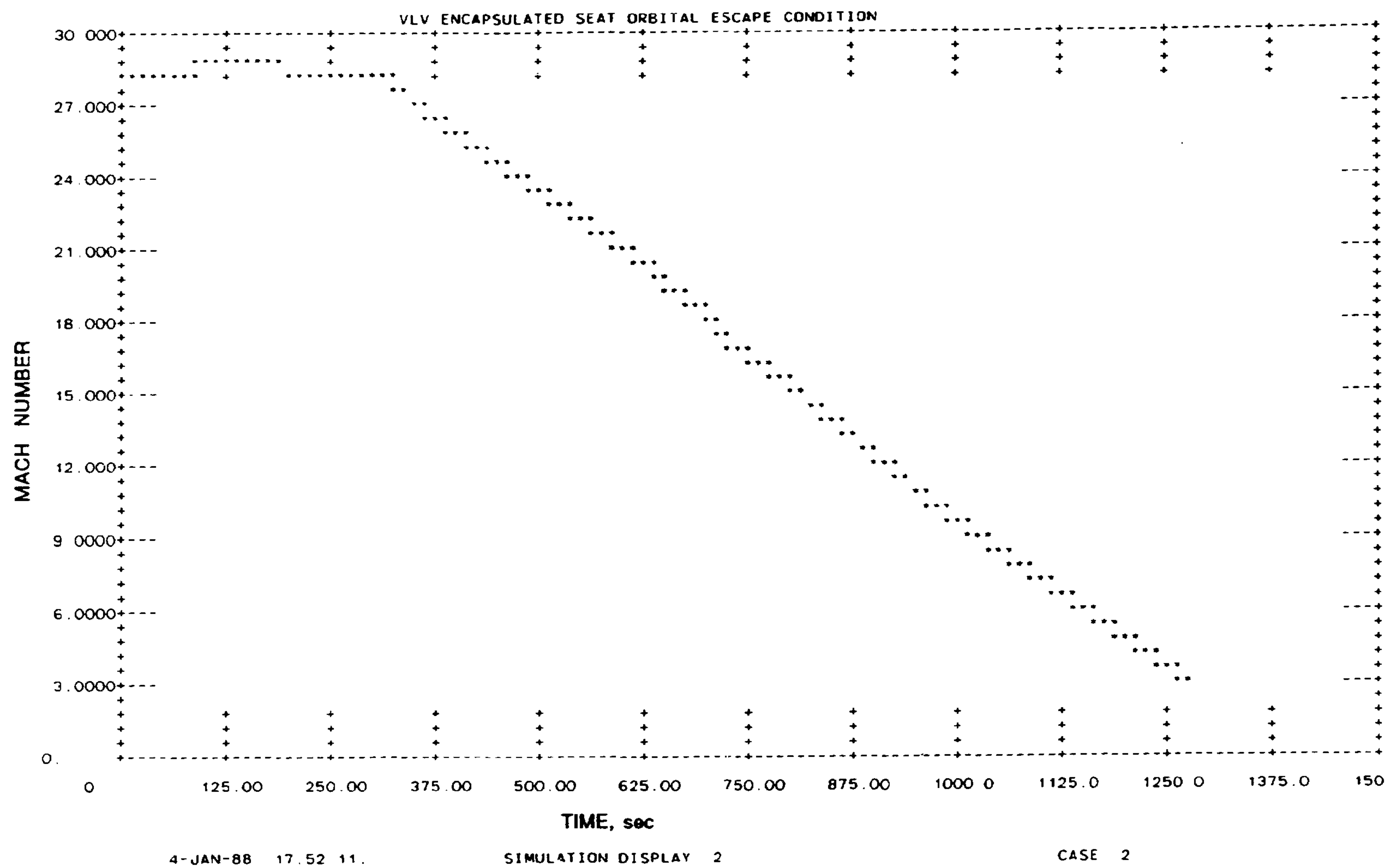


Figure B-16. Mach Number Versus Time for Single-Place Encapsulated Seat, Escape Condition 4

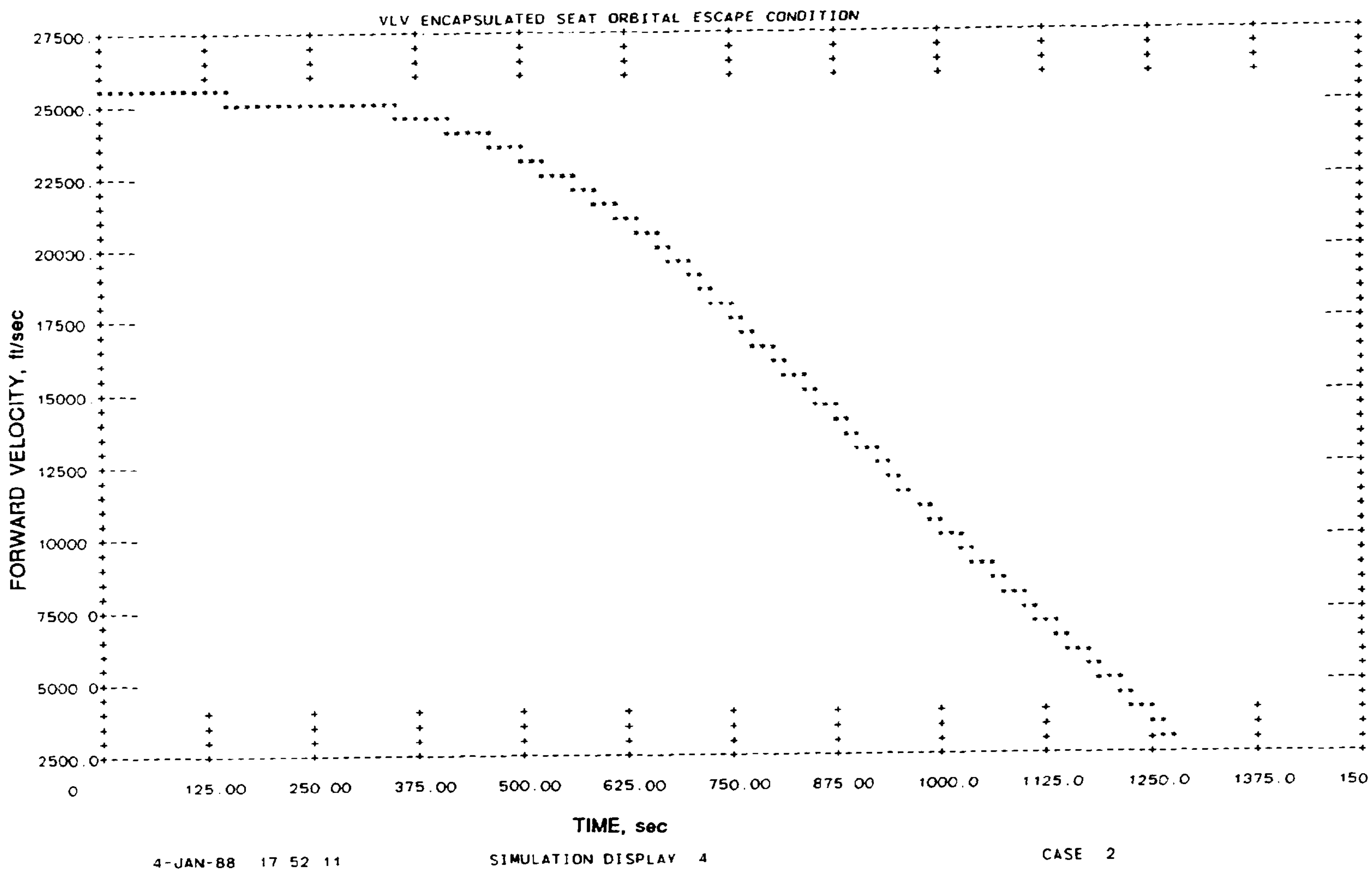


Figure B-17. Forward Velocity Versus Time for Single-Place Encapsulated Seat, Escape Condition 4

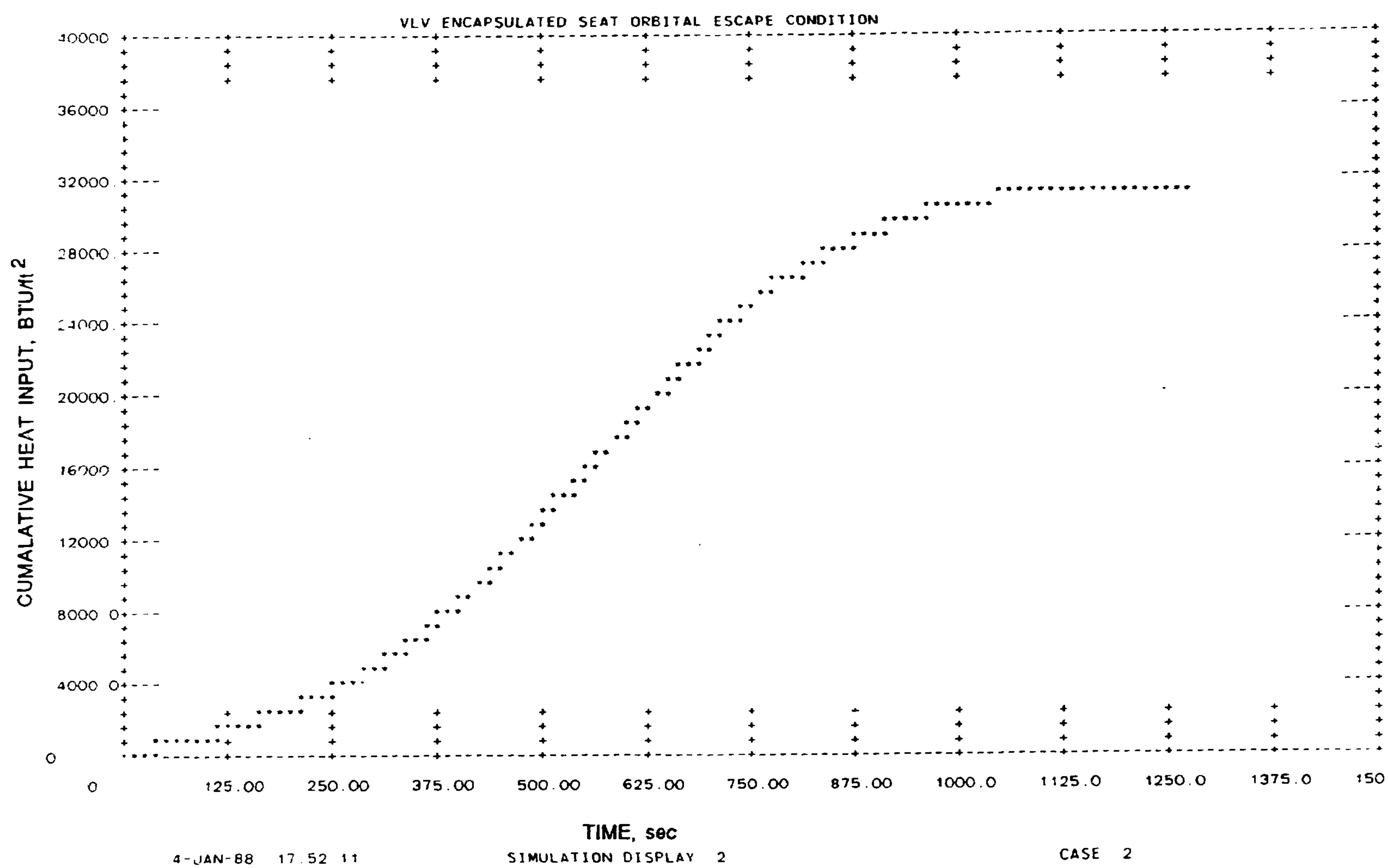


Figure B-18. Cumulative Heat Versus Time for Single-Place Encapsulated Seat, Escape Condition 4

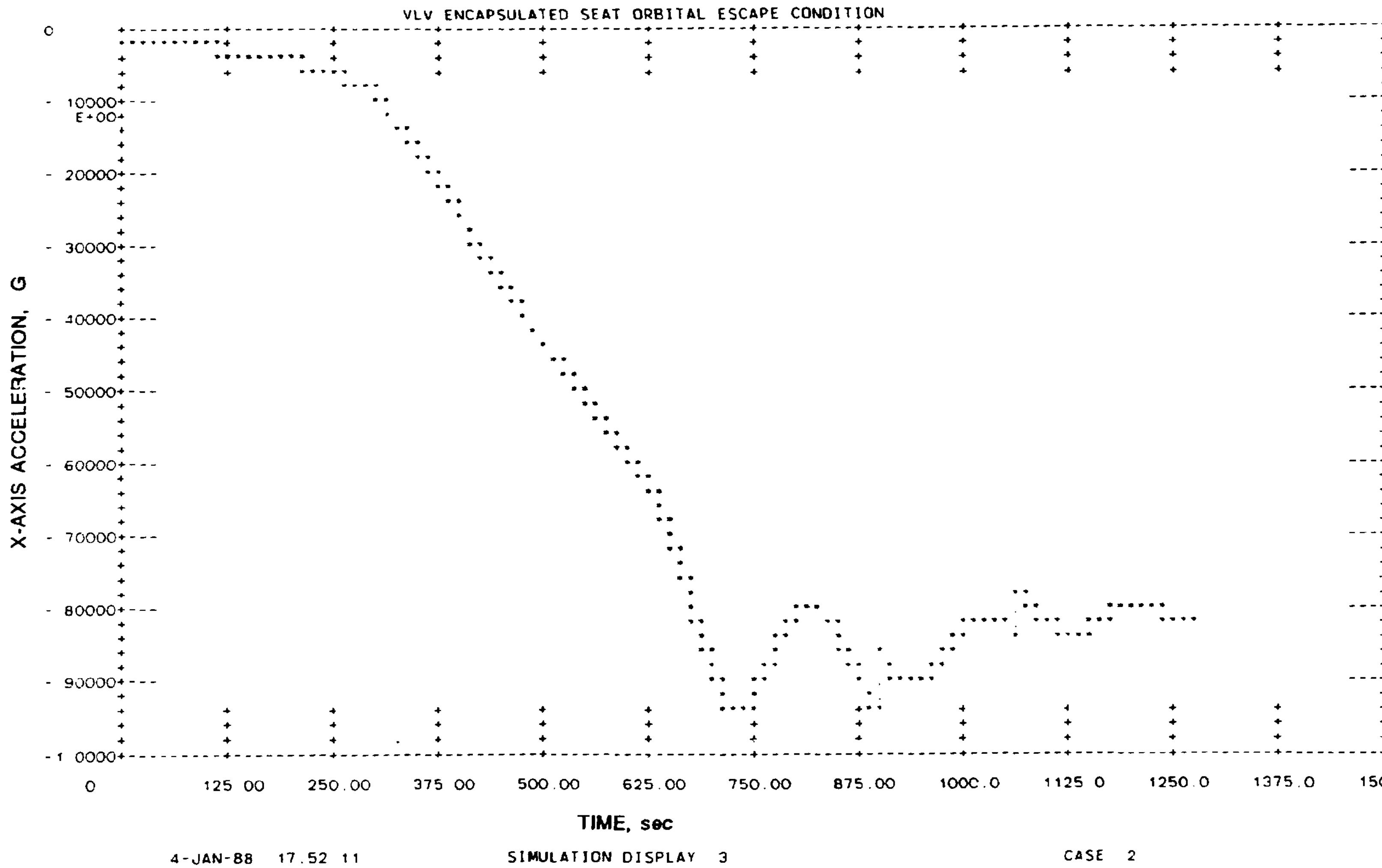


Figure B-19. X-Axis Acceleration Versus Time for Single-Place Encapsulated Seat, Escape Condition 4

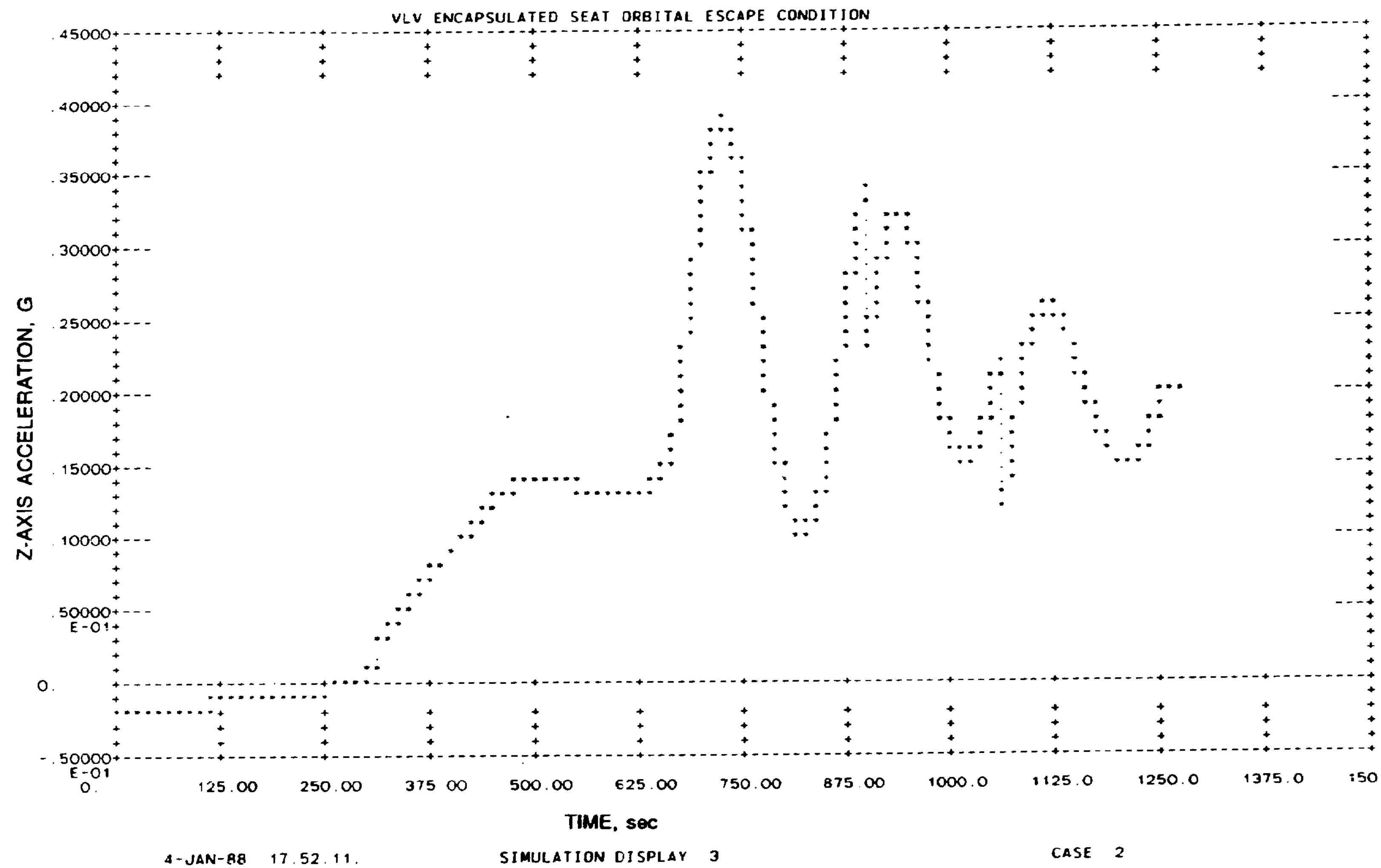


Figure B-20. Z-Axis Acceleration Versus Time for Single-Place Encapsulated Seat, Escape Condition 4